

Janes

Investigation of the airflow in an
acoustic jet at resonance.

J 23
Thesis

Library
U. S. Naval Postgraduate School
Annapolis, Md.

UNIVERSITY OF CALIFORNIA
LIBRARY

A Thesis

Submitted in Partial Fulfillment of the Requirements
for the Degree of

Master of Science in the Department of
Chemistry

By

Walter J. Jones

March 1951

TABLE OF CONTENTS

Summary	1
Introduction	3
Terminology	5
Related theory	6
Description of apparatus and procedure	13
Results and discussion	22
Conclusions	25
Bibliography	26

LIST OF FIGURES

- Figure 1. Schematic Diagram
- Figure 2. Mechanical Layout
- Figure 3. Resonator Open End Modification with "Wall Static" Impedance
- Figure 4. Mechanical Transfer Function
- Figure 5. Mechanical Transfer Function
- Figure 6. Resonator Wall Static and Total Pressure Distribution in Axial Direction
- Figure 7. Total Pressure Distribution in Axial Direction Resonator Axis of Symmetry
- Figure 8. Resonator Wall Static Pressure Distribution for $\alpha = 10$ and $\beta = 10$ at $\theta = 0$
- Figure 9. Resonator Wall Static Pressure Distribution for $\alpha = 10$ and $\beta = 10$ at $\theta = 0$, with Distance from Resonator Open End as a Parameter
- Figure 10. Effect of α and β on Wall Static Pressure at the Resonator Surface
- Figure 11. Effect of Frequency on Wall Static Pressure at the Resonator Surface for Fixed Resonator Length
- Figure 12. Effect of Frequency on Wall Static Pressure at the Resonator Wall for Selected Values
- Figure 13. Determination of Resonant Frequency for Basic Resonator Configuration by Measuring the Wall Static Pressure at the Resonator Surface
- Figure 14. Determination of Resonant α for Fixed β , Resonator Configuration
- Figure 15. Graph for Basic Resonator Configuration
- Figure 16. Resonant Wall Static Pressure, Wall Static Pressure

Smart /13/, Wood /9/, Morse /1/, and Refs 4, 6, 7), it appears that further analysis and investigation is needed in the case of the acoustic jet.

Previous investigations (Refs. 1, 2) have concentrated largely on directly relating the acoustic phenomena to thrust and have shown among other things that the acoustic jet device is extremely sensitive to open-end edge conditions, and that it is possible to increase the thrust by increasing the amplitude of the forcing vibration. A broad program of further quantitative and qualitative determination of the flow fields in acoustic jets is needed for the attainment of adequate understanding of this special problem and for further insight into the general characteristics of pulsating flow. Pressure surveys, paralleling the thrust investigations, are needed.

A mechanical pulsator was designed and built by the University of Minnesota Mechanical Engineering Staff for use in a broad program of research in pulsatile phenomena employing both sinusoidal and instantaneous oscillations. This program was made possible by United Aircraft Research Department support. The pulsator was readily made available for the present work which was proposed as a preliminary phase of the broad program.

The primary objectives were twofold; (1) construction

of the flow patterns and behavior employing tufts, smoke, and dust as flow visualization techniques, and thus establishing, if possible, the salient characteristics of the flow associated with the basic reactor configuration in the available range of amplitude of pulsator vibration; (2) Obtaining mean static and total pressure data, using liquid manometer measurements, showing mean pressure distribution in the basic reactor and jet excited by the highest available (about one inch) amplitude of pulsator vibration.

The work was carried out in the Engines Laboratory of the Mechanical and Aeronautical Engineering Departments of the University of Minnesota, under the guidance of Dr. T. A. Hall. The author wishes to express his appreciation for the use of the pulsator, which was made possible through United Aircraft Research Directorate support, and to express his thanks and appreciation to the following: Dr. T. A. Hall, for his direction and counsel; Professor F. E. Murphy, for his suggestions; and Dr. Professor E. L. Kelly, for his suggestions and assistance.

SYMBOLS

p_g	Gage mean static pressure, inches of water, referred to atmospheric pressure.
p_o	Gage mean total pressure, inches of water, referred to atmospheric pressure.
P_a	Ambient atmospheric pressure, inches of mercury, absolute.
t	Ambient atmospheric temperature, degrees Fahrenheit. Also used for time in seconds.
T	Absolute temperature, degrees Rankine. Thrust is lb.
x	Distance along resonator axis, in inches, measured from the plane normal to the axis, at the open end of the resonator, towards the closed end (piston).
$-x$	Same as x except measured in the other direction (external).
z	General variable for distance along resonator measured from plane of closed end.
L	Resonator length in inches.
ϕ	Angular position in degrees in any plane normal to the resonator axis; referred to a zero line extending from the axis vertically upward; and increasing in a clockwise direction as the observer faces the closed resonator end from the open end. This is used in the tables (see Table VII and subsequent tables through XII) to indicate the position and direction of the probe at the introduction point. Thus, in Table XII, the static wall pressure at the probe introduction point is at the top of the pressure data column for 0° and for 30°, and is at the bottom of the pressure data column for 150° and for 270°.
r	Radial distance from the resonator axis in inches, positive along the line defining ϕ ; negative along the line defining $\phi \pm 180^\circ$.

r ¹	Distance, in inches, measured from the inside resonator wall along a line extending through, and normal to, the resonator axis. Thus it has its largest magnitude at the resonator axis. It is not used negatively.
nr & n	Revolutions per minute of the pulser crankshaft unless reference is to some other mechanism.
c	Piston stroke in inches measured from head-end down center.
h	Crank radius in inches.
l	Center to center length of connecting rod in inches.
θ	Angular position of the pulser crank from head-end dead center.
v	Linear velocity variable.
u	Velocity paralleling resonator axis, positive in direction of positive x.
a	Speed of propagation of a sound wave.
f	Frequency, cycles per second.
ω	Angular velocity, radians per second.

Terms Used in Tables

Basic Resonator Configuration. Refers to the basic resonator configuration as described in detail under Apparatus.

Wall Static. Refers to the instrumentation arrangement described, and so referred to, in the section on Apparatus.

Internal Instrument. Refers to the instrumentation arrangement described, and so referred to, in the section on Apparatus.

External Instrument. Refers to the instrumentation arrangement described, and so referred to, in the section on Apparatus.

Square. Used with reference to the open end edge of the separator, it signifies that the tube was cut squarely off in a plane normal to the axis and that the resulting edge was not unduly tapering.

Sharp. Used with reference to the open end edge of the separator, it signifies that the edge was tapered to a sharp edge consistent with the end of the inner wall.

RELATED THEORY

The elementary theory, concerning the possible resonant modes of vibration in air columns traversed by plane pressure waves or impulses, is well established and appears in most textbooks on sound (Refs. 7, 8). It should suffice to review briefly the theory directly related to the resonator configuration which was used in this work, namely, a circular tube open at one end and closed at the other.

Single Resonator Theory

Pressure impulses (pulses) in a tube by plane surfaces normal to the axis are generally assumed to propagate as plane pulses or waves. These waves reflect from area discontinuities (corners). Upon encountering a plane wall, as a closed end of a tube, they reflect without change of phase. Upon encountering an "aperture", as at the open end of a tube, they reflect with a one-hundred eighty degree change of phase, i.e., compression waves are reflected as rarefaction waves and rarefaction waves are reflected as compression waves. These waves travel at local sonic velocity, or higher with respect to the air particles and depending upon their strength. When the tube length and frequency of vibration are related in such a way that reflected waves return

experiment that a "good connection" is needed. Thus, the generally accepted formula for the fundamental frequency of such a resonator is (p. 1).

$$f = \frac{a}{2(L + 0.6r)} \quad (1)$$

Illustrative Fire-Stream Diagram

For this also, the action, time interval in the single theory (fire stream), and under the additional assumption that the compressions and rarefactions are weak plane waves produced instantaneously at the fire-stream location of the fire, it is of interest to follow the progress of these compressions and rarefactions in an illustrative fire-distance diagram ("fire stream") such as is shown in Figure 2. The small arrow indicates the direction of the velocity increments Δu , and is equal to Δu , the arrow. The circled numbers indicate the strength of the wave at each Δu . Obviously, during the time interval Δt into the initial situation is that a state of equilibrium is reached when the energy level of the fire stream is higher with the loads, and at this point the waves have reached their maximum strength.

Piston Motion

The motion of the piston is of interest because it originates the pulse and determines the boundary conditions of the closed end. The pulsator employed in this investigation was designed with a conventional crank-pin and connecting rod linkage with provision for adjusting the piston stroke in the range of zero to one inch. Thus (ref. 10), the piston displacement from dead-end dead center (-) is:

$$x = r + L - (r^2 - L^2 \sin^2 \theta)^{1/2} - L \cos \theta \quad (2)$$

where r is the center-to-center length of the connecting rod; L is the crank radius; and θ is the angular position of the crank face measured from center. The approximate piston velocity (\dot{x}) in feet per second is:

$$\dot{x} = 0.000307 \pi (\sin \theta + \frac{L}{r} \sin 2\theta) \quad (3)$$

where π is RPM; L is in inches; and $r = L/\delta$. The approximate acceleration of the piston velocity (\ddot{x}) in feet per sec.² is:

$$\ddot{x} = 0.000107 \pi^2 (\cos \theta + 2 \frac{L}{r} \cos 2\theta) \quad (4)$$

where the units are as before.

Additional Wave Theory

Reinforcement of a cumulative effect is taken place at resonance, so that the final level of a low strength is difficult to predict. If the coordinates are transferred to the new coordinate system, it is evident that the approach velocity of the flow relative to the free surface is the same as the velocity of the wave. It may be observed further that the final level of a low strength and temperature distribution is the same. It is shown in subsequent texts that the local velocity of wave propagation is a function of the local absolute temperature, thus (Ref. 15):

$$a = \sqrt{g r M} = \sqrt{r p / c} \quad (1)$$

where the units must be consistent.

There are certain fundamental physical differences between compressive waves and expansive waves. Some of these are ordinarily considered negligible when treating weak isolated waves, but are of no small account when dealing with strong waves or the conditions produced by the repetitive passage of a great many weak waves. It may be shown (Ref. 15) that if a finite, continuous, compressive wave is started, such as by a piston moving sinusoidally in a tube, and point of this disturbance, then it

of is a small step wave, such propagates itself at the local speed of sound, relative to the fluid at that point, and will therefore overtake the initial increment of the wave, after a finite time, to form a discontinuity such that the compression takes place practically instantaneously. This must occur because the value of a compression wave is characterized by an increase in density and temperature (and thus velocity of propagation) over the unperturbed conditions. The time is needed for this to occur is given by (Ref. 17, p. 17).

$$t = (2/\sqrt{1 + 1}) (1/v) \quad (3)$$

where $n = (d\rho/dt)_{\text{all}}$, the maximum slope of the pressure-volume-distance curve. If the maximum slope of the velocity-distance curve for the piston be taken as a crude approximation of that value, one finds, for the case of one-inch piston stroke and 1005 ft/sec related to a nine foot long resonator, that the time required to form a discontinuity would be approximately 0.009 seconds, while the time required for the pulse to reach the open end of the resonator would be approximately 0.004 seconds so that a discontinuity is not formed. If, if the maximum slope n revealed the point where the actual slope of the velocity-distance curve for the flow over the piston was still or below three the value for the piston,

would appear near the open end of the resonator.

The reverse situation is true for an expansion wave. Each succeeding segment of such a wave finds itself travelling in a slightly smaller radius than the segment immediately preceding it, and thus at a slightly lower rate. This expansion wave tends to become less steep and to spread out. There is no natural mechanism for the formation of a discontinuous expansion wave (ref. 18). The approach flow velocity relative to an expansion wave remains an invariant of velocity increases, decrease non-dimensional mass impart a sediment.

Measurement of Oscillatory Pressures

Special problems arise in connection with the simplest measurements of oscillating pressures. The fluid is essentially flowing in one direction of the resonant transmission system and this is a non-isentropic process involving flow work and accompanying viscous losses. The natural frequency of the instrumentation, if selected, may completely distort the actual picture. The full features are characteristically attenuated, amplified, and lag.

Attenuation refers to the pressure drop along a tube due to viscous forces (not resonance effects) and is generally calculated on the basis of Poiseuille's law of viscous resistance

which is given as (Ref. 11):

$$\partial p / \partial x = -(128 / \pi) (\mu' / D^3) Q \quad (17)$$

where p is the instantaneous pressure at any point in the connecting tube; x is the distance along the tube measured from the entrance; μ' is the mean fluid viscosity; D is the tube diameter; Q is the volumetric flow at any point in the tube. Equation (16) is combined with the non-steady, one-dimensional form of the equation of continuity, in Ref. 11, to obtain a solution for values of the loss in real amplitude of pressure for a steady-state pressure measurement device. Simplified variation of the entrance is assumed (about the zero pressure), and it is assumed that the instrumentation has been chosen so as to avoid unwanted resonance effects.

An earlier work (Ref. 12) offers a solution which provides the variation with time, and is perhaps more suited to estimation of the attenuating effect on mean pressure when $\omega \gg \omega_0$.

In this case, equation (17) was integrated directly, assuming constant volume flow per unit time, to obtain the pressure drop ($0 \leq x \leq L$):

$$P_1 - P_2 = (128 \mu' / \pi D^3) L Q \quad (18)$$

and for turbulent flow ($2000 \leq Re \leq 100,000$),

$$T_1 = T_2 = 1/6 (1/\pi)^{7/4} \frac{(\mu_2)}{\rho_0} \frac{(\gamma_2)^{1/4}}{D^{9/4}} \quad (18)$$

where the units must be consistent, Q is the mass rate of flow, and the properties are taken values at the entrance and average exit respectively. A procedure for determining the rate of flow was given in a previous paper for laminar flow, above the critical Reynolds number was taken as 2000. Thus,

$$Q \Delta_1/I \leq 3.1 \cdot 10^{-6} \quad (19)$$

For laminar flow, where Q is in inches per Δ_1/I is pressure drop in inches of mercury per foot of tubing.

Discussion is the basis of the value of the constant in the preceding equation is the corresponding value at the entrance of the transmission line. Thus, in the preceding case 1949, the pressure drop is calculated just the effect of natural frequency oscillations in the measuring system. This is also particularly obvious in March 27, 1949 (p. 12). The electrical system is used. The effect of system noise and without significant interference from the system, as well as the effect of the system of system noise on the system. The electrical method of measuring the transmission line is also given in the paper.

possible piston stroke magnitudes available in the range of 100 to 150 mm. The values of piston stroke used in this investigation were, in mm: 0.254, 0.254, 0.254, 0.254, 0.254. These values included the minimum and the maximum for the apparatus. A single pin bearing connecting rod (overall length, center to center) was connected to a crank shaft. The crank shaft was provided with a guide bearing. The pin, secured at the head end of the crank shaft and fitted into a steel cylinder mounted in an end frame. The piston, connecting rod, crank shaft, and guide bearing were all of aluminum. The piston had about two thousand clearance in the cylinder when cold, and had no provision for sealing against the leakage of oil from the cylinder and filling. The cylinder was fitted with a 1/2 inch diameter (corresponding to the inside diameter of the pressure) was eight inches long. The head was two inches of the cylinder was widened to six inches to provide the bearing surface.

The basic principle of operation, as described in the text and table, refers to the principle of operation as described in the paragraph. The test and the principle, tested using (22.5 inches long; 2.0 inches diameter, 1.5 inches diameter) were tested together as detailed separately on three separate supports.

(See Figure 1). One end was inserted in the pulsator receiver
studier. The ballast coils were sealed with corked tape which
was easily removable. Small patches of the same material were
used to seal orifices which were not in use. The overall length
of the resonator, measured from the open end to the mean piston
position (one-inch stroke), was found to be two hundred and
four-hundredths inches, or nearly nine feet. The plastic tube
ends were square-cut, and in particular, the edge of the open
end of the resonator was square-cut or blunt. Sixteen orifices
(0.070 in., drilled with sharp no. 50 drill) were spaced six
inches apart, in a straight line along the upper surface. These
were numbered as follows and through aluminum standoffs at the
open end. The orifice near the open end was at a distance
from the end of about 3/16 inches to permit attachment of pipe. The
other sixteen orifices of the same diameter were drilled at
stations 3, 7, 11, and 17. These, together with the top orifice,
were given equidistant angular spacing (90° apart). The tube was
carefully aligned with the axis of the pulsator piston. The
resonator opening was eight feet from the facing wall and the
resonator center axis was thirty-four inches from the floor.

The main modification to the basic resonator configuration,
considered in this work, was that used to investigate the
effect of a sharp versus a blunt open-end edge (Figure 5). This

(5/16 inch ID). Circular pieces of rubber tubing, approximately fifty-fifty inches long, were used to connect the two Y pipe tubes to liquid manometers. The liquid chambers were 10 cm.

The manometers employed were of the liquid, draft gauge type (Figure 1). The one which was used for all the two pressure readings and with the lower chamber in position during the full static experiments was a laboratory type, No. 11. The scale was graduated, however, in inches of water. The range was from 0 to fifteen inches with only the last 10 inches each part of the scale marked. A small three and one-half, draft chamber (2 1/2 inches), filled with distilled water, was used with the lower chamber against the specimen, except for occasional readings at the No. 1 which were off the scale. These manometers could be read to the third decimal place on the horizontal scale and to the second decimal place on the vertical scale. All readings were taken as referred to the top of the scale.

The pressure measurement instrumentation was of three types: (1) wall static, used for most of the measurements of static pressure at the chamber wall; (2) internal pressure, used for the static and total head pressure transducer mounted inside the chamber; (3) external pressure, used for pressure measurements in the jet.

be obtained. This probe was made by taking a
length of the 1/2 inch diameter ID, and turning down
the 1/2 inch diameter ID.

- (2) Another steel probe similar to (1) was made of
steel tubing. This probe was about 1/2 inch
diameter ID, 1/2 inch diameter ID, and 1/2 inch
diameter ID.
- (3) A total head probe was made from brass tubing with
the same dimensions as (2) except that it was
about 1/2 inch length, overall. The end of this probe
was again expanded to the 1/2 inch shape, except
that the end was of 1/2 inch. A one-half inch
diameter blunt-tipped, and was 1/2 inch diameter
ID. The end of the probe was 1/2 inch diameter ID,
and approximately 1/2 inch diameter ID,
and 1/2 inch ID, the end of the probe was 1/2
inch ID. This probe was turned down to the
total head probe because of its shape.
- (4) A total head probe was also made from brass tubing, with
the same dimensions as (2). It was 1/2 inch
ID and turned off with a 1/2 inch and polished down to
the shape of a 1/2 inch. A total head probe was

The hole of the probe three-eighths of an inch from the end. This hole is three-eighths of an inch in diameter which is only slightly different from the inside diameter of the probe (three-eighths of an inch). This probe has been referred to as a cylinder-type total head probe since it is based on the fact that stagnation occurs at the leading edge of a cylinder placed normal to a steady flow.

The external pressure - configuration consisted of an arrangement as shown in Figure 4. The probe fitted snugly into a one inch opening in a mounting plate in the support frame. It could be slid back and forth using a spring steel mechanism on the probe for positioning. Vertical positioning could be made by raising the mounting plate up and down between the two vertical support bars. When positioned vertically, the mounting plate position was fixed by a clamp arrangement. The vertical support bars could be rotated about a vertical axis providing another degree of freedom. The external pressure probes were connected to the probe chamber by a 1/8-inch pipe of outside diameter (7/16 in. ID) and a one-way stop-check.

A description of the probe and its external pressure attachment follows.

with increased internal resistance from the open end of the resonator.

The reversal of dominant total head values at the resonator mouth suggests that the air inflow and outflow is truly alternating over the whole open end, and that the air motion is not solely atmospheric total pressure, since it is mostly drawn from the surrounding atmosphere at the inlet, and the air performs the oscillation associated with the total oscillations over a relatively short time. At high frequencies, "the two effects (inflow and outflow of the air as a jet) are of course in reality alternating, and only appear to be simultaneous in consequence of the inability of the eye to follow such rapid changes".

The total head reversal, as a wave front, entered the chamber from the resonator open end, where the transition point between the atmosphere inside the major portion of the resonator which appears to be primarily oscillatory, and the jet and jet flow which appears to be primarily an external circulation system strongly placed in the region of the atmosphere from end. Visual observations (Figure 21) suggested that much of the surrounding air, drawn toward the resonator open end, joined the jet flow from the vicinity of the jet flow system without

centering the resonator. It appeared that this air jet caused a depression and tended to support the jet flow.

The velocity difference between static and total head values (approximately three and one-half times as large) is one just inside the resonator pipe and also indicated other velocities in the order of one hundred twenty-five feet per second. The mean velocity at one foot outside the resonator is indicated as about eighty feet per second, and the mean velocity at a distance of three feet outside the resonator is indicated as about sixty feet per second. These values compare with the velocity of a standard piston velocity of eight and one-half feet per second and 0.375 in. piston stroke.

Lateral Pressure Gradients

A comparison of the mean static pressure distribution along the wall of the resonator with the radial mean static pressure distribution is shown in Figure 3. The axial gradient is greater than the wall gradient except that considerably lower gradients exist just along the wall as the open end of the resonator is approached. The values are very small all over near the closed end. A sharp reversal of the static pressure takes place just inside the pipe end, which is due to the effect of the edge vortex system. The divergence of the

axial and wall static pressure distributions correlates with the visual observations of greatly increased jet particle lengths near the open end, assuming that the latter are an indication of increased jet molecule path lengths.

Profiles of mean static pressure distribution inside the resonator are shown in Figure 11. These profiles, with the exception of that for Station One, were obtained by adding from two pairs of opposed distributions at each station as a check upon the symmetry of the pressure distribution.

Profiles of mean static and total pressures in the external jet area (horizontal plane), are presented in Figure 12 for distances one-half, two and four-half inches from the open end of the resonator.

Total mean profiles are presented in Figure 13. These profiles appear to be small except in the region near the open end of the resonator.

Variation in Mean Static Pressure Distribution with Station Location

The mean static pressure distribution along the resonator wall for various magnitudes of piston stroke is shown in Figure 3. The pressure gradient is generally smaller with piston stroke, although the original pressure distribution pattern is

retained. The cross plot of pressure versus distance is shown in Figure 9. It appears that the variation is essentially linear in this range. This agrees with the results of the linear pressure piston effect results presented in Ref. 1 for a linear accelerometer without any modification. The greatest rate of change is positive and is near the closed end, but the local rate of change is negative and is near the open end.

Variation in Pressure for a Blunt and Sharp Edge Open-End Accelerator Configuration

The difference in wall static pressure distribution for accelerators with blunt and sharp edge open-end accelerometer configurations is shown in Figure 10. Somewhat lower values were obtained with the tapered edge.

Variation in Wall Static Pressure with Frequency for a Blunt Accelerator Length

The variation of wall static pressure distribution along the accelerometer wall is shown in Figure 11 for various frequencies and values. A cross plot of measured pressure with calculated distance is shown in Figure 12. It is evident that a longitudinal pressure gradient is produced much like the pressure

condition was stationary. Test figures, arriving at the speed of the regulator, will be in the range of 100 and feed out the central jet. They produce an oscillated wave of pulsating the low pressure circle flow pattern of the jet as shown in figures 21, 22, and 23, and show the degree of symmetry in the flow.

Limitation of Results

The main factor affecting the results obtained was the instrumentation detail with reference to the diameter and length of all tubes and constrictions used in the pressure measurement system. Quantitative evaluation of the data would depend on detailed calculation of the system losses along the lines provided in the discussion of related theory (A-2, 11, 12, 13, 14, 15).

It was found that a basic requirement was the exercise of extreme care with regard to the uniformity of the test equipment at each station. During the course of the investigation, some experimental errors were discovered.

Good reproducibility of results was maintained. The results did not appear to be sensitive to the small variation

REFERENCES

1. Corb, J. L.: "First Interim Report on the Investigation of Intermittent Flow;" Report No. A-1500-1; United Aircraft Corporation, East Hartford, Conn., 27 September, 1940.
2. Christy, H. E.: "Relation between Acoustic Resonance and Dynamic Thrust," Master of Science Thesis, Aeronautical Engineering, University of Minnesota, August 1939.
3. Logan, Joseph W., Jr.: "Suggested Forms of Air Jet Motors Utilizing Intermittent Combustion," Parts I and II, Project Squid, Report No. CAL-15, Cornell Aeronautical Laboratory, Inc., Buffalo 21, New York, 20 February, 1940.
4. Rodiger, George and Arnold, Edward J.: "The Construction of Wave Diagrams for the Study of Gas-Dynamic Flow-Fields," Part I, Report No. CAL-15, Project Squid, Cornell Aeronautical Laboratory, Inc., Buffalo 21, New York, 10 March, 1940.
5. Rodiger, G., Logan, J., and Doolittle, W.: "Investigations of Acoustic Jets," (a) Part I, Report No. CAL-15, (b) Part II, Report No. CAL-16, Project Squid, Cornell Aeronautical Laboratory, Inc., Buffalo 21, New York, 10 March, 1940.
6. Rayleigh, John W. S.: "The Theory of Sound;" Vol. 1, Dover Publications, New York, 1940.
7. Lamb, Philip M.: "Vibration and Sound;" McGraw-Hill Book Co., Inc., 1933.
8. Laguard, C.: "On the Excitation of Sound into a Circular Tube, with an Application to Loudspeakers," Arch. Polytech. 25 (Elect. Eng. Ser. 1, No. 7) Trans. Chalmers Univ. Tech. Stockholm 70, 5-17 (1941). In English. The case of a fluid piston source or rigid tube is treated theoretically.
9. Ray, H. S.: "Textbook of Sound;" 2d. Ed. and 2nd, 1918.

10. Milne, J. W. "Aircraft Engine Design;" McGraw Hill Book Co., New York, 1942.
11. Horall, H. C. "Interference of Oscillatory Pressures in Instrument Lines;" Transactions of the ASME, Vol. 72, No. 5; July, 1950.
12. Salberg, Israel. "The Response of Pressure Measuring Systems to Oscillating Pressures;" AIAA 71-1010, January, 1950.
13. Leary, C. "Physical Review, 70, 40, 1947.
14. Pope, H. "The Effect of Motion;" John Wiley and Sons, Inc., New York, 1950.
15. Liepmann, H. W., and Fink, H. W. "Aerodynamics of Compressible Fluids;" John Wiley and Sons, Inc., New York, 1948.
16. Milne, J. W. "Effect of Drop in Timing in Aircraft Instrument Installations;" AIAA 71-1010, January, 1950.

TABLE I
 DEFINITION OF RESONANT FREQUENCY FOR BASIC
 RESONATOR CONFIGURATIONS
 (Resonator Wall Mean Static Pressure Data)

Instrumentation: *Wall Static Piston Stroke: 0.072 in.
 End Ridge Shape: Square Resonator Length: 107.1 in.

Sta. No. X (in. from open end)	H _a	t	0	10
			00	102
Ref.	H _a	t	h _g	h _g
1854	29.24	89	-1.82	47.25
1858	29.24	89	-1.81	5.42
1867	29.24	89	-2.01	5.77
1874	29.24	89	-2.04	5.80
1879	29.24	85		5.15
1884	29.24	89	-2.12	5.15
1892	29.24	89	-2.12	5.30
1898	29.24	85		5.58
1901	29.24	88	-2.11	5.40
1905	29.24	85		5.40
1911	29.24	85		5.45
1914	29.24	89	-2.00	5.31
1918	29.24	89	-2.05	5.18
1925	29.24	85		5.95
1940	29.24	89	-1.80	5.00
1951	29.24	89	-1.53	4.80
1970	29.24	85	-1.72	46.80

*See Apparatus and Nomenclature

*See Limitations

TABLE 11
 DETERMINATION OF RESEARCH REFINERY *SHARP LEE
 RESEARCH CORPORATION**
 (Refractor Wall Near Static Pressure Data)

Instrumentation: *Wall Static *Piston Static: 0.375 in.

Sta. No.	1	2
A	0	104
H _A	23.33	23.33
L	80	80
L	102.4	102.4
End Edge Shape	Sharp	Sharp
REF	h _g	h _g
1735	-2.25	18.20
1800	-2.59	3.70
1808	-2.51	3.50
1813	-2.87	3.70
1820	-2.87	3.70
1828	-2.87	3.30
1830	-2.80	4.10
1843	-2.10	4.30
1852	-3.21	4.35
1860	-2.05	4.40
1864	-2.05	4.35
1867	-2.00	4.40
1875	-2.60	4.10
1884	-2.60	3.30
1888	-2.60	3.70
1904	-2.52	3.10
1908	-2.45	3.40
1917	-2.25	17.10

*See Apparatus and Specifications

**See Limitations

TABLE III

VARIATION OF RESONATOR WALL LOSS COEFFICIENTS WITH FREQUENCY

Instrumentation: Wall Static Piston Stroke: 0.075 in.
 End Edge Shape: Square Resonator Length: 107.1 in.
 Resonator: Basic Configuration

Hz	1949	1970	1980	1997	1916	1935	1950	1991
$\frac{1}{\text{ft}}$	30.24	30.22	30.27	30.24	30.27	30.22	30.24	30.24
$\frac{1}{\text{ft}}$	30	30	35	30	37	38	30	33
Sta. No.	1	2	3	4	5	6	7	8
1	0	-2.46	-3.00	-3.27	-3.49	-5.42	-3.30	-5.71
2	0	-1.76	-2.27	-2.41	-2.55	-2.84	-2.25	-1.22
3	12	-1.78	-2.24	-2.37	-2.51	-2.81	-2.31	-2.02
4	12	-1.53	-1.30	-1.20	-1.12	-3.30	-1.02	-1.73
5	32	-1.32	-1.53	-1.13	-1.20	-1.14	-1.44	-1.73
6	30	-1.27	-1.30	-1.14	-1.02	-1.02	-1.22	-1.70
7	30	-1.00	-1.20	-1.11	-1.73	-1.34	-1.72	-1.38
8	42	-2.17	-2.10	-2.73	-2.49	-2.33	-2.72	-2.31
9	18	10.14	10.00	10.00	10.04	2.00	10.02	10.01
10	74	1.07	11.11	1.10	1.03	10.67	10.20	10.21
11	60	1.00	2.30	2.33	2.44	2.17	2.12	2.22
12	60	2.10	2.10	2.33	2.33	2.22	2.11	2.24
13	72	2.20	2.50	2.70	2.72	2.72	2.42	2.22
14	72	2.20	2.32	2.22	2.70	2.21	2.21	2.22
15	60	2.21	2.10	2.22	2.12	2.12	2.12	2.22
16	60	2.20	2.21	2.22	2.12	2.02	2.02	2.22
17	30	2.07	2.21	2.72	2.02	2.12	2.22	2.22
18	102	11.07	12.71	12.02	11.22	12.12	11.01	11.22

*See Appendix and Unpublished

*See Limitations

*Modified Configuration (Wall Loss) at Station Number 10
 (See Figure 3)

TABLE IV

MEASUREMENTS WITH WALL STATIC PRESSURE TAP,
CORRECTED EFFECT OF ROSS AND SYLVESTER

Instrumentation: Wall static modified
Piston Stroke: 2.075 in.
Resonator Length: 100.4 in.
Resonator: Flange configuration plate modified

End Edge Shape	Sharp	Sharp	Square
R_2	20.27	20.30	20.21
t_2	38	38	38
h_2	1001	1001	1001
Sta. No.	R	h_2	h_3
1a	0	-0.00	-0.10
1	5	-0.00	-0.73
2	0	-0.51	-0.35
3	12	-0.41	-0.37
4	20	-0.12	-0.17
5	20	-0.73	-0.47
6	20	-0.13	-0.10
7	20	-0.08	-0.04
8	20	-0.02	-0.00
9	30	-0.07	-0.12
10	30	0.42	0.14
11	30	1.00	0.03
12	60	1.00	0.01
13	72	0.00	0.00
14	90	0.10	0.07
15	90	0.14	0.00
16	90	0.00	0.00
17	90	0.00	0.00
18	100	0.00	0.01

See Apparatus and Formulation

*See Limitations

TABLE XX

RESPIRATOR WALL LOSS DATA - FRACTIONAL SATURATED STEAM

WITH 74.4 MM. FACTOR OF SAFETY*

Instrumentation: Wall Static Resistor: *Table Configuration
 End Edge Shape: Square Resistor Length: 107.4 in.

Piston Stroke, in.	0.051	0.293	0.542	0.792	0.970	
R_0	1908	1908	1908	1908	1908	
h_a	29.42	29.42	29.42	29.42	29.42	
t	53	53	53	53	53	
Sta. No.	R	h_3	h_4	h_5	h_6	
1	0	-0.18	-0.05	-0.06	-0.71	-0.31
2	5	-0.09	-0.02	-1.16	-1.08	-0.15
3	12	-0.03	-0.07	-1.20	-1.75	-0.37
4	12	-0.02	-0.54	-1.19	-1.71	-0.20
5	21	10.03	-0.72	-0.51	-1.18	-1.00
6	30	-0.05	-0.17	-1.27	-1.35	-0.18
7	30	-0.03	-0.10	-0.08	-1.51	-1.35
8	42	10.05	-0.11	-0.50	-0.70	-0.35
9	42	0.27	10.03	10.03	10.03	10.03
10	51	0.12	0.35	0.65	0.73	0.50
11	60	0.19	0.65	1.30	1.54	1.02
12	60	0.22	0.90	1.30	1.60	0.10
13	72	0.21	1.00	1.00	2.52	0.28
14	72	0.20	1.31	2.08	3.27	1.20
15	84	0.22	1.40	2.70	3.70	1.30
16	90	0.10	1.00	3.11	3.31	1.00
17	96	0.33	1.51	3.72	3.31	0.31
18	102	10.02	11.41	10.71	10.12	10.00

*See Apparatus and Nomenclature

**See Limitations

TABLE IV

C-3-101, INTERNAL MECHANISM TEST, WALL POSITION DATA*

Instrumentation: *Internal Flared Piston Stroke: 0.972 in.
 Resonator: *Basic Configuration. End Flange Shape: Square
 Resonator Length: 107.1 in.

Std. No.	2	3	18	19	17
Ref.	1992	1992	1992	1997	1992
\bar{u}_a	23.47	23.32	23.32	23.36	23.32
\bar{u}_b	23	23	23	23	23
\bar{u}_{**}	20	20	20	20	20
Type of Probe	1-head-3	1-head-3	1-head-3	0-1-4	1-head-3

Probe Opening Facing Toward Piston:

r^1	b_0	b_1	b_2	b_3	b_4
0.25	-0.31	-0.28	12.17	12.42	12.27
0.75	-0.41	-0.43	5.15	5.45	5.30
1.75	-0.49	-0.49	5.13	5.46	5.40
2.75	-0.52	-0.51	5.17	5.46	5.43
1.75	-0.44	-0.42	12.32	12.41	12.45

Probe Opening Facing Away from Piston:

r^1	b_0	b_1	b_2	b_3	b_4
0.25	-0.35	-0.32	12.53	12.42	12.27
0.75	-0.55	-0.53	5.52	5.43	5.37
1.75	-0.54	-0.53	5.62	5.55	5.53
2.75	-0.60	-0.41	5.65	5.54	5.23
1.75	-0.55	-0.35	12.65	12.54	12.22

*See Apparatus and Documentation.

**See Limitations.

***Refers to wall position of probe introduction. See Documentation.

TABLE II

102" TOTAL PRESSURE SURVEY ALONG CENTER LINE

Instrumentation: *Internal traverses, cylinder Probe (1)
 Resonator: *Basic configuration Piston Stroke: 0.870 in.
 Resonator Length: 107.4 in. End Edge Shape: Square

Distance from			
tube wall, in. (r ¹)		2.75	2.75
r _a		23.25	23.25
t _a		22	22
r _{***}		22	22
Probe Opening Orientation		Facing Piston	Away from Piston
Sta. No.	Alt.	r _o	r _o
1	1992	-1.41	-0.67
2	1993	-1.53	-0.56
3	1991	-0.62	-0.17
4	1990	-0.56	-0.62
5	1998	-0.75	-0.45
6	1999	10.00	-0.20
7	1993	9.62	10.79
8	1997	1.11	2.67
9	1995	1.40	1.71
10	1997	2.50	2.40
11	1992	3.10	3.75
12	1991	3.50	3.50
13	1992	4.35	4.73
14	1992	5.10	5.10
15	1993	5.53	5.51
16	1992	5.90	5.92
17	1992	5.25	5.25
18	1991	6.40	16.40

*See Apparatus and Nomenclature.

**See Limitations.

***Refers to wall position of probe introduction. See Nomenclature.

TABLE XII

LATERAL MEAN PRESSURE DATA*

(Traverse in Horizontal Axial Plane)

Instrumentation: *External Pressure
 Recorder: *Basic Configuration
 Recorder Length: 107.4 in.

Piston Stroke: 3.972 in.
 Open End Gauge: Square

r	0.5	0.5	0.5	3.5	3.5	3.5
Re	1001	1001	1001	1001	1001	1001
T_a	29.12	29.42	29.42	29.12	29.42	29.42
t	21	21	21	21	21	21
Type of Probe	(5)	(5)	(6)	(5)	(5)	(6)
ρ_{max}	300	300	300	300	300	300
r	$h_o(in)_m$	$h_o(ut)_m$	h_o	$h_o(in)$	$h_o(ut)$	h_o
-4.0	-0.08	-0.25		-0.08	-0.25	
-3.5	-0.24	-0.42	-0.52			
-3.0	-1.05	-0.45	-0.87	10.30	-0.45	-2.90
-2.5	-1.00	-0.64	-2.23			
-2.0	-0.50	-0.41	-2.13	0.41	-0.31	-0.69
-1.5	-0.43	-0.41	-1.70			
-1.0	-0.70	-0.20	-1.27	0.70	-0.12	-0.50
-0.5	-0.20	-0.28	-1.00			
0.0	-0.34	-0.18	-1.85	0.37	-0.12	-0.60
10.5	-0.28	-0.20	-1.84			
1.0	-0.37	-0.34	-2.37	0.05	-0.22	-0.80
1.5	-0.47	-0.41	-2.60			
2.0	-0.71	-0.44	-2.60	1.11	-0.50	-1.10
2.5			-2.40			
3.0	-0.58	-0.75	-2.80	10.70	-0.45	-0.70
3.5			-2.18			
4.0			-0.16			
5.0			-0.03	-0.03	-0.14	-0.14
6.0			-0.03			-0.05
7.0						-0.02

*See Apparatus and Nomenclature.

*See Li Station.

+refers to wall position or direction of probe introduction,
 "in" is positive or side from which probe is introduced. See
 Nomenclature.

*Total loss pointing either toward the piston (in) or away from
 the piston (out).

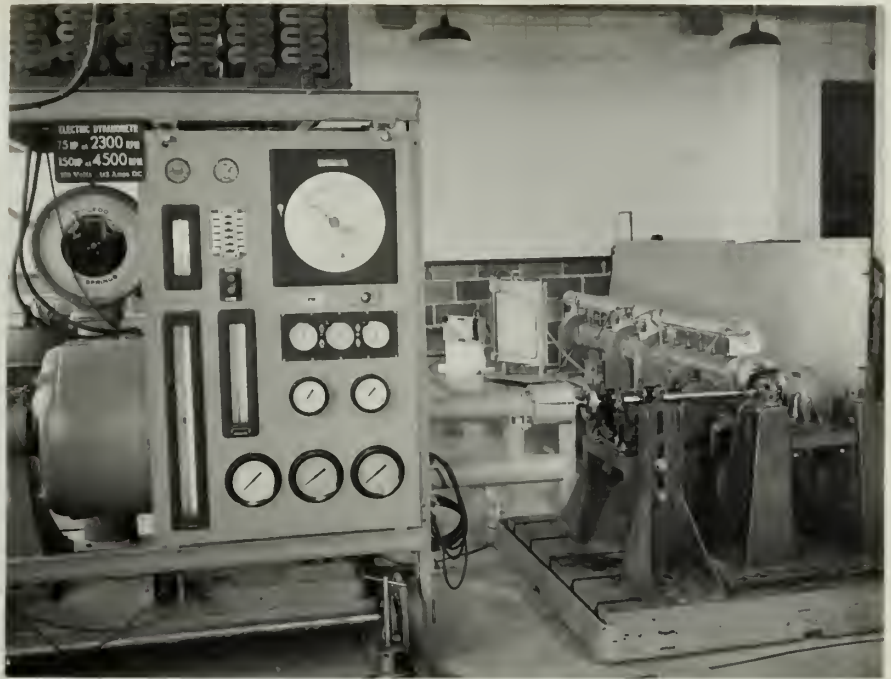


Figure 1. Vacuum furnace.

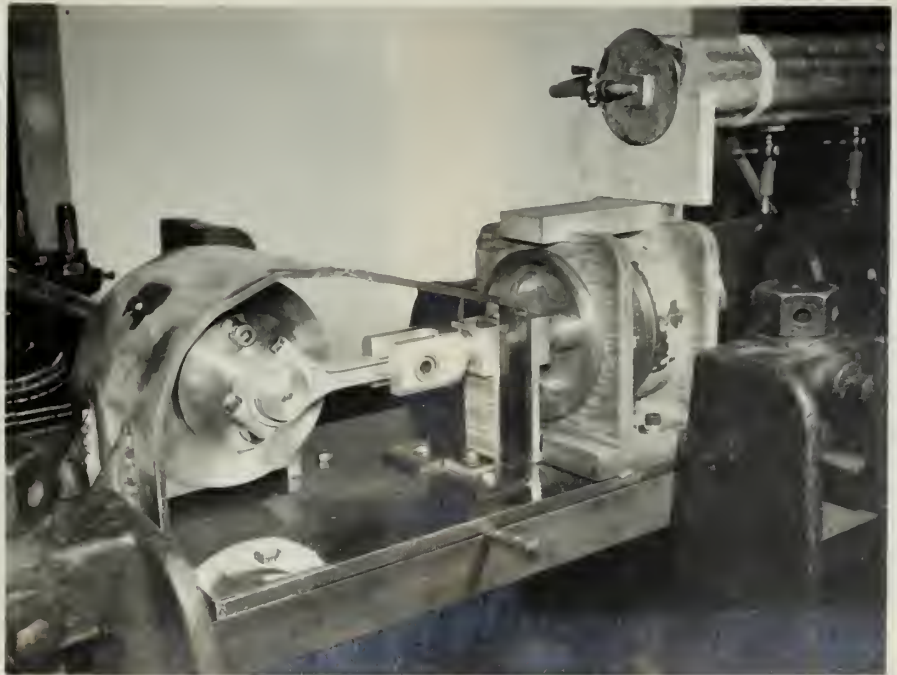


Figure 2. Machining of turbine.

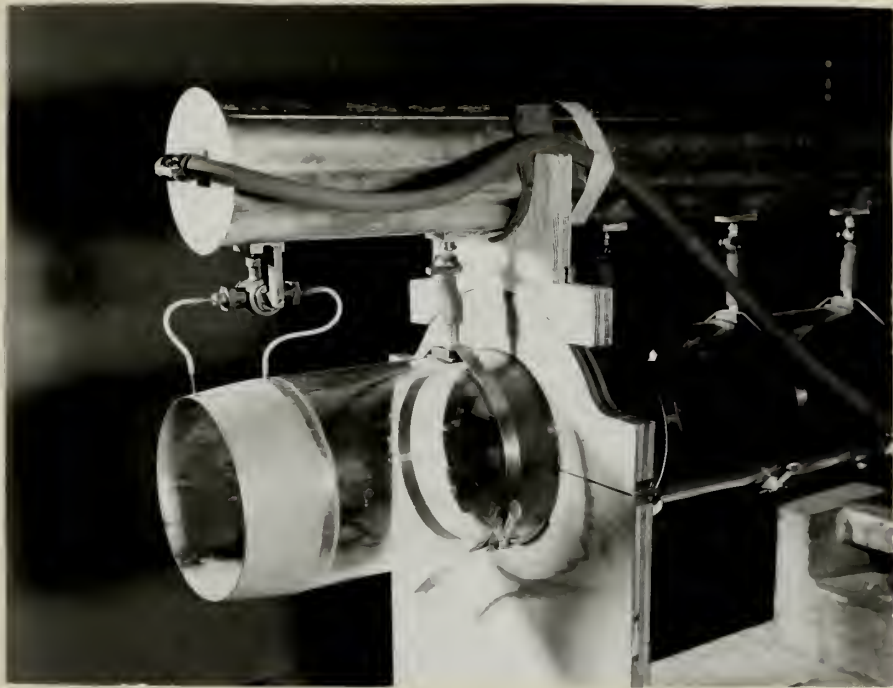


Figure 3. Test Water Open and Discharge with
"Wall Jet" Instrumentation.



Figure 4. Sectional Diagram
Apparatus.



Figure 5. Internal Diagram
Apparatus.

FIG. 5. RESONATOR MEAN STATIC AND TOTAL PRESSURE DISTRIBUTION IN AXIAL DIRECTION
(DATA FROM TABLES VII, VIII, X)

- △ WALL STATIC PRESSURE
- AXIAL STATIC PRESSURE
- ▷ AXIAL TOTAL PRESSURE FACING PISTON
- ◁ AXIAL TOTAL PRESSURE FACING AWAY FROM PISTON

PISTON STROKE = 0.978 IN.

GAGE MEAN PRESSURE, IN. H₂O

MEAN POSITION OF PISTON HEAD END

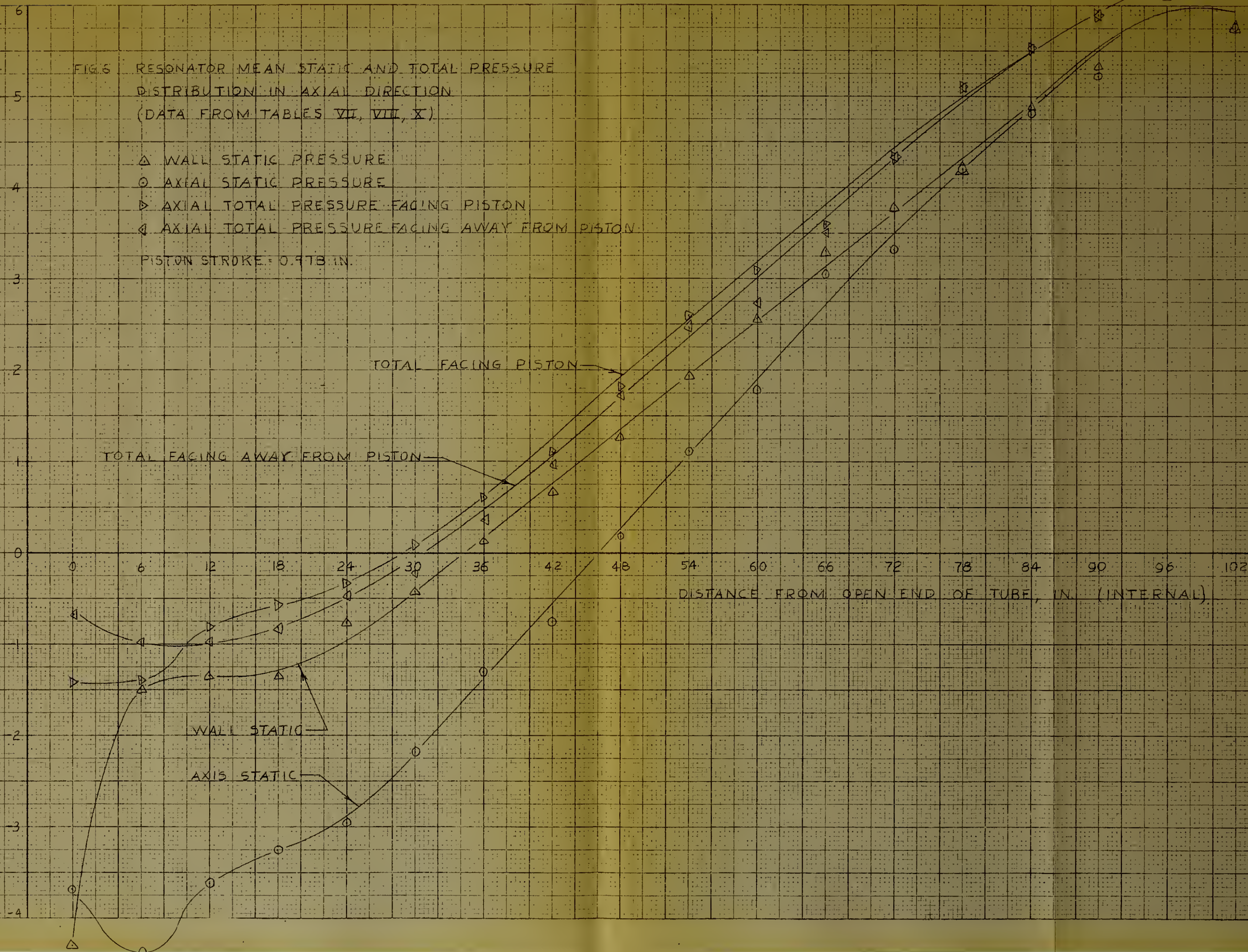
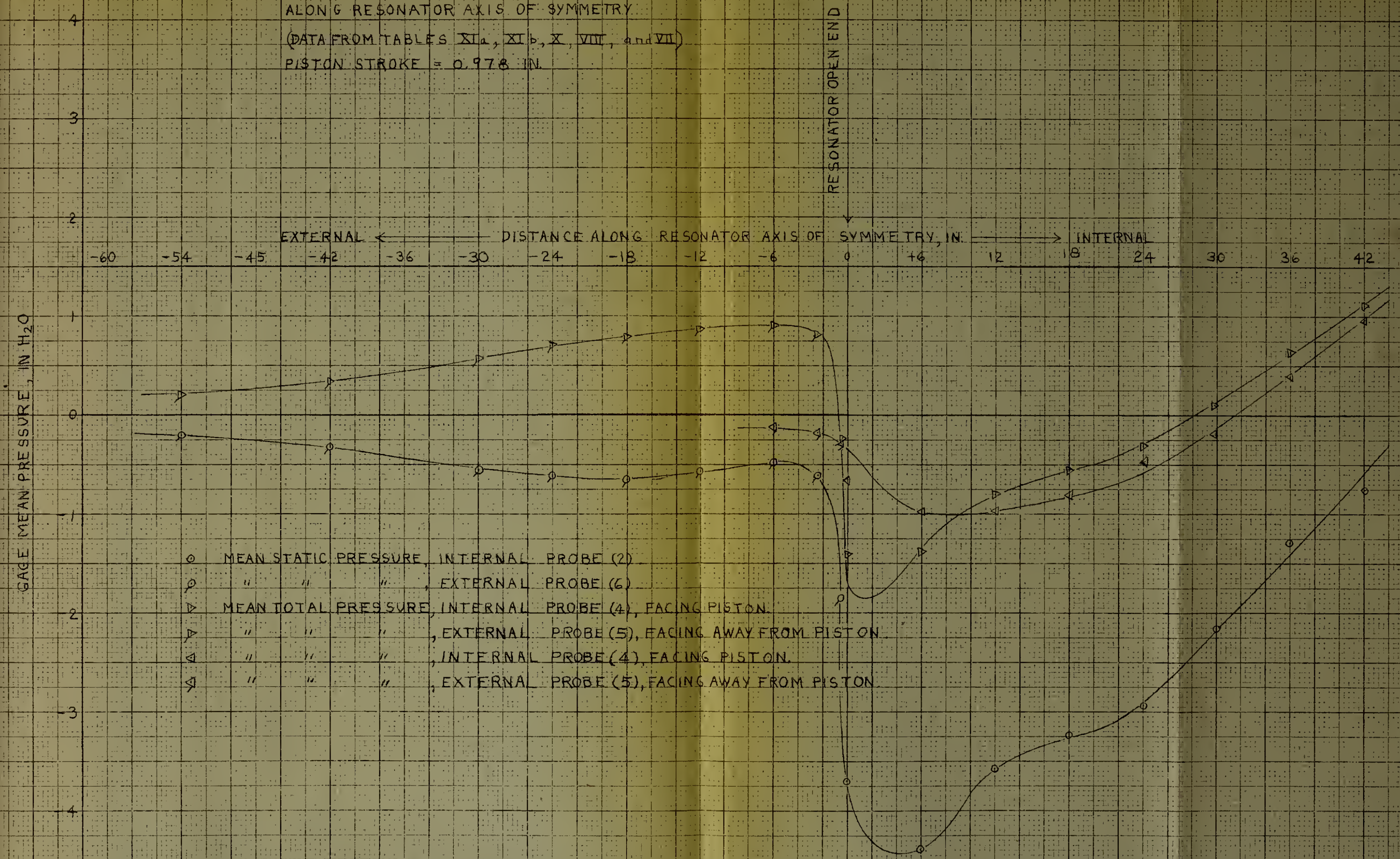


FIG. 7 MEAN PRESSURE DISTRIBUTION IN JET
 ALONG RESONATOR AXIS OF SYMMETRY.
 (DATA FROM TABLES XIa, XIb, X, VIII, and VII)
 PISTON STROKE = 0.978 IN.



○ MEAN STATIC PRESSURE, INTERNAL PROBE (2)
 ○ " " " " EXTERNAL PROBE (6)
 △ MEAN TOTAL PRESSURE, INTERNAL PROBE (4), FACING PISTON.
 △ " " " " EXTERNAL PROBE (5), FACING AWAY FROM PISTON.
 △ " " " " INTERNAL PROBE (4), FACING PISTON.
 ☆ " " " " EXTERNAL PROBE (5), FACING AWAY FROM PISTON.

FIG. 8 RESONATOR WALL STATIC PRESSURE DISTRIBUTION
FOR VARIOUS MAGNITUDES OF PISTON STROKE
(DATA FROM TABLE V)

X = 0.054 INCHES PISTON STROKE

▽ = 0.292 " " "

□ = 0.542 " " "

△ = 0.762 " " "

○ = 0.978 " " "

X ▽ □ △ ○ EXPERIMENTAL ERROR

RESONATOR WALL GAGE MEAN STATIC PRESSURE, IN. H₂O

MEAN POSITION OF PISTON HEAD - END

DISTANCE FROM OPEN END OF RESONATOR, IN. (INTERNAL)

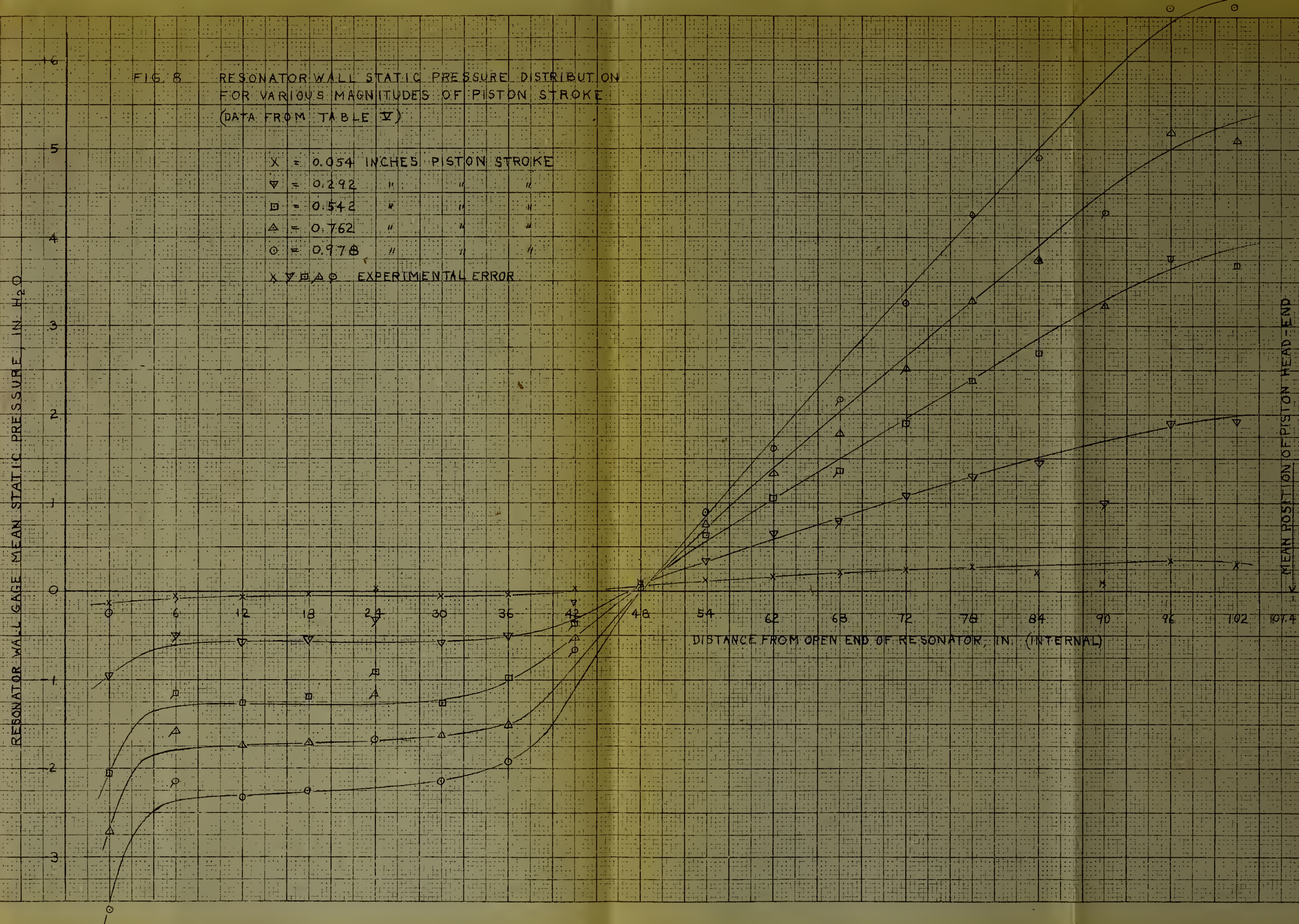


FIG. 9 RESONATOR WALL MEAN STATIC PRESSURE
VERSUS PISTON STROKE WITH DISTANCE
FROM RESONATOR OPEN END AS A
PARAMETER - (DATA FROM TABLE V)

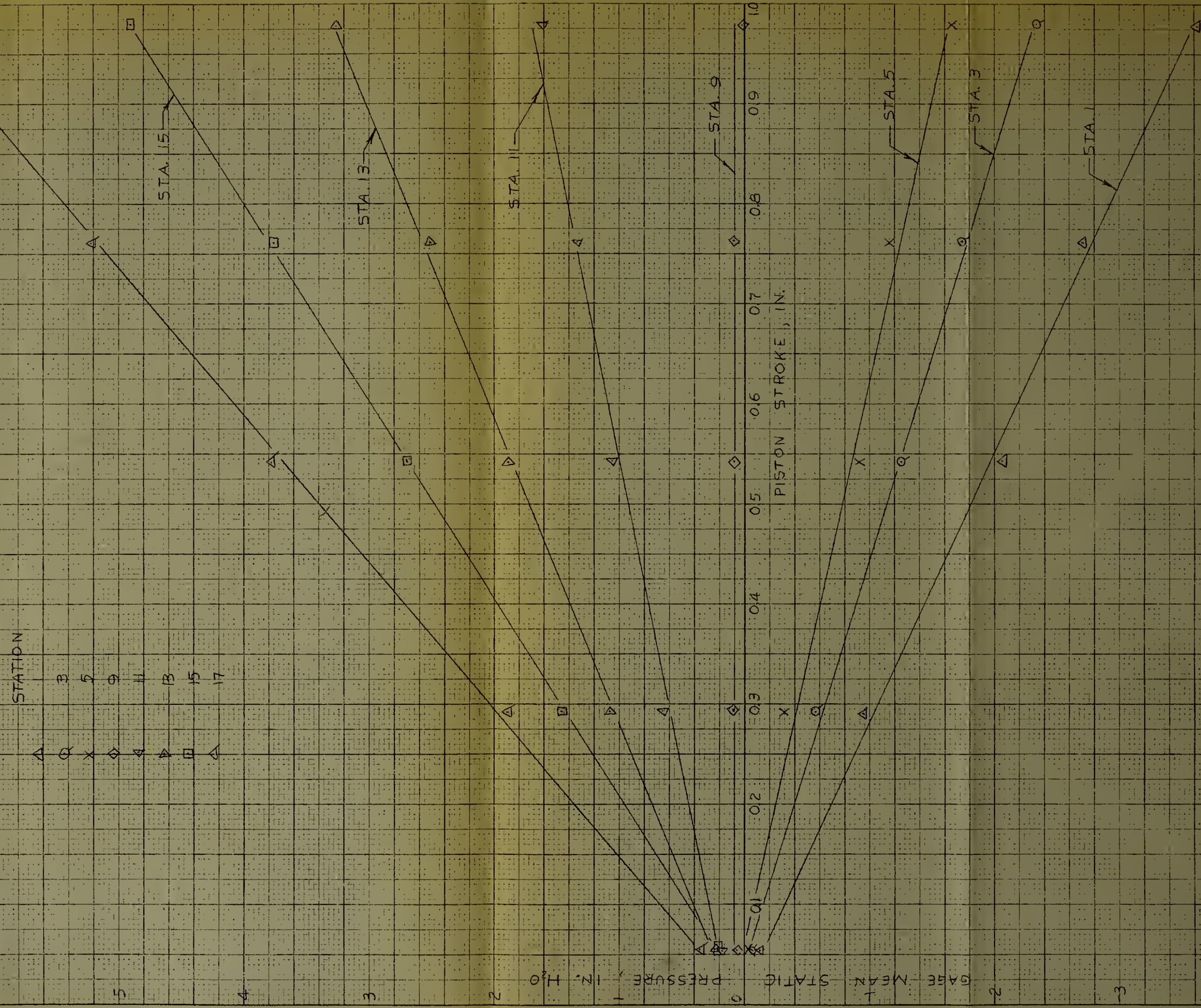
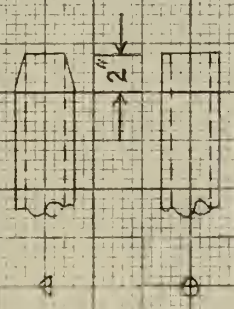


FIG. 10 EFFECT OF OPEN END SHAPE ON MEAN STATIC PRESSURE AT THE RESONATOR SURFACE

(DATA FROM TABLE IV)



Q Δ EXPERIMENTAL ERROR

PISTON STROKE = 0.878 IN.

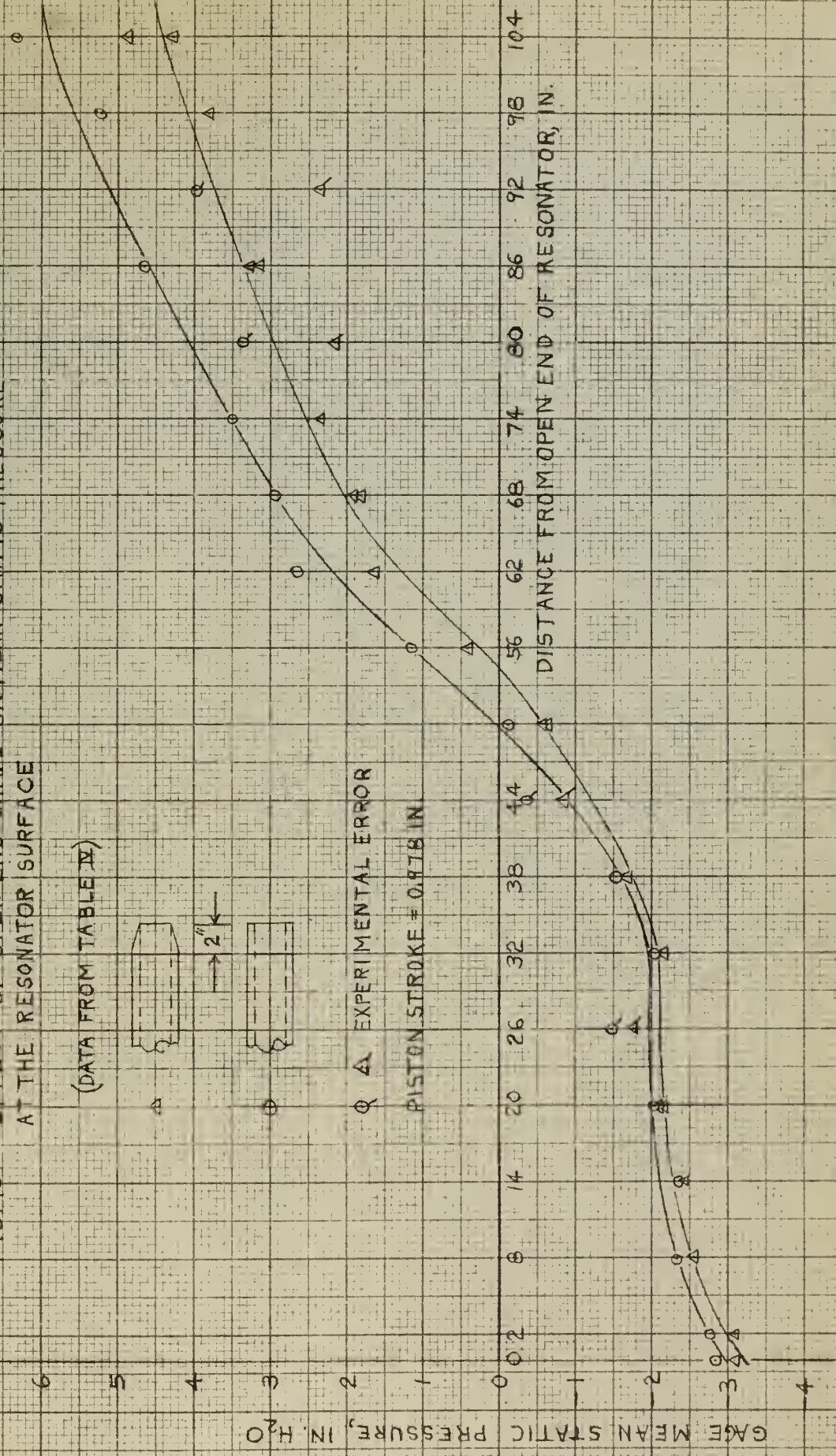


FIG. 11 EFFECT OF FREQUENCY ON MEAN STATIC PRESSURE
AT THE RESONATOR SURFACE FOR FIXED RESONATOR LENGTH
(DATA FROM TABLE III)

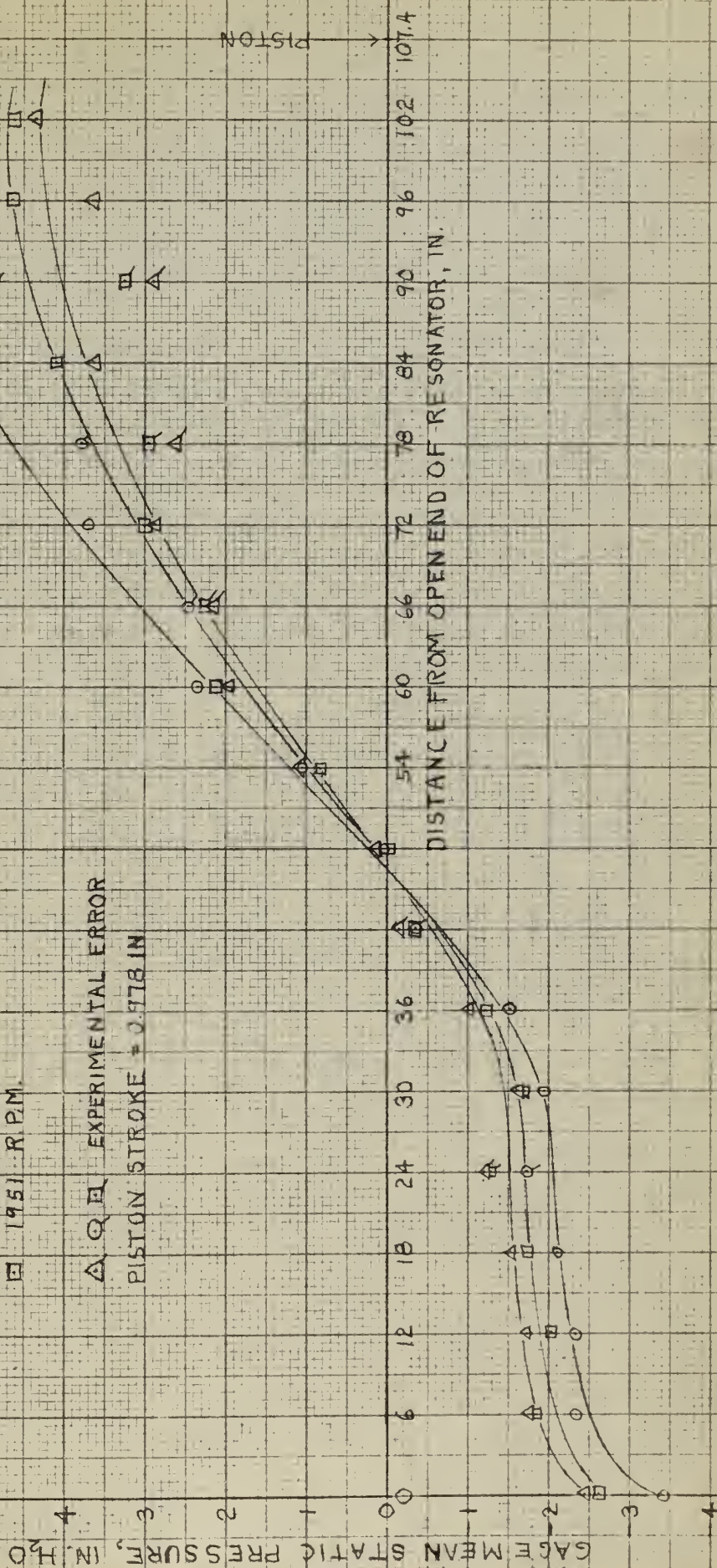
△ 1848 R.P.M.

○ 1903 R.P.M. (RESONANCE)

□ 1951 R.P.M.

△ Q □ EXPERIMENTAL ERROR

PISTON STROKE = 0.778 IN.



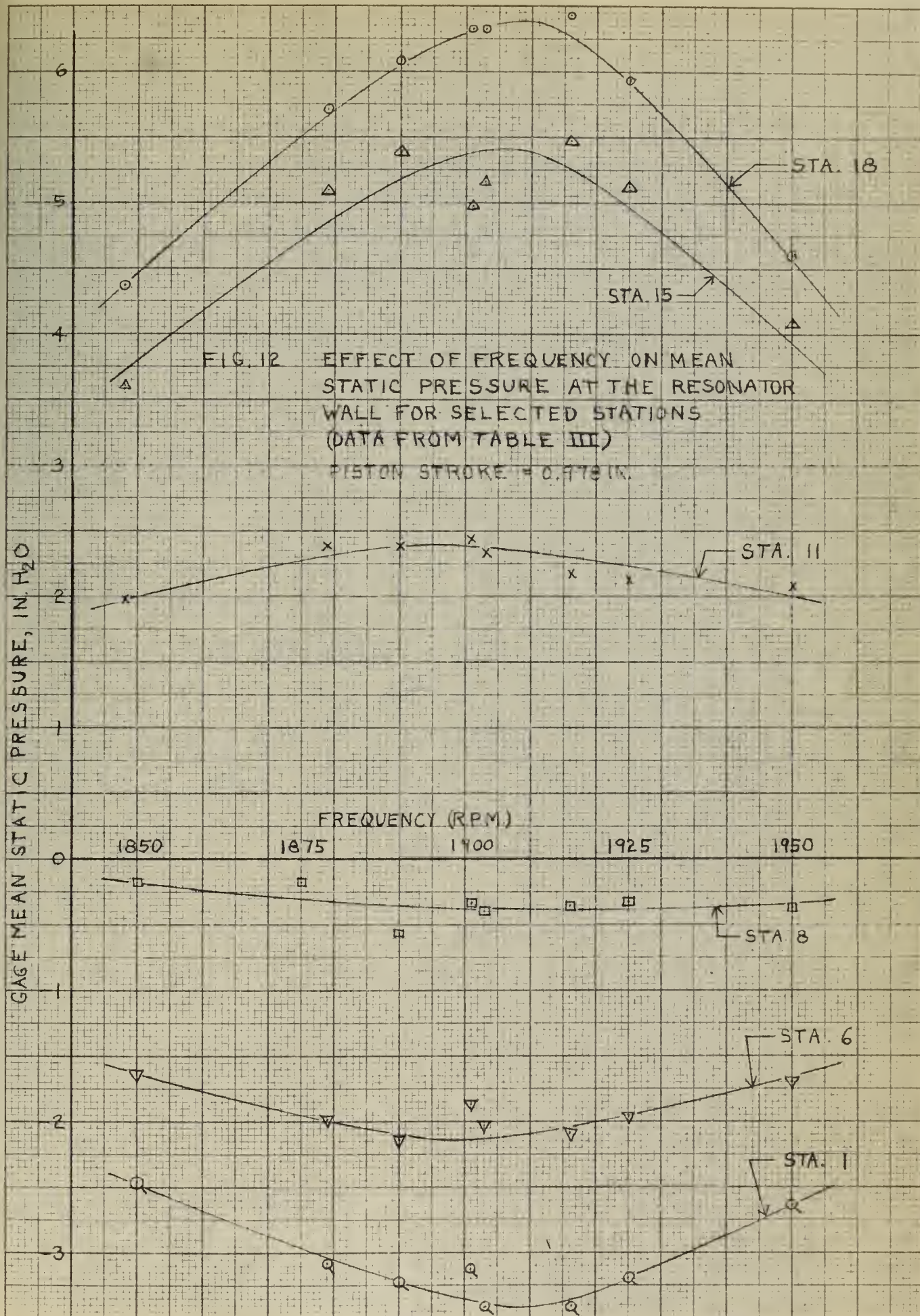


FIG. 13 DETERMINATION OF RESONANT FREQUENCY
FOR BASIC RESONATOR CONFIGURATION BY
MEASURING THE MEAN STATIC PRESSURE
AT THE RESONATOR SURFACE
(DATA FROM TABLE I)
PISTON STROKE = 0.978 IN.

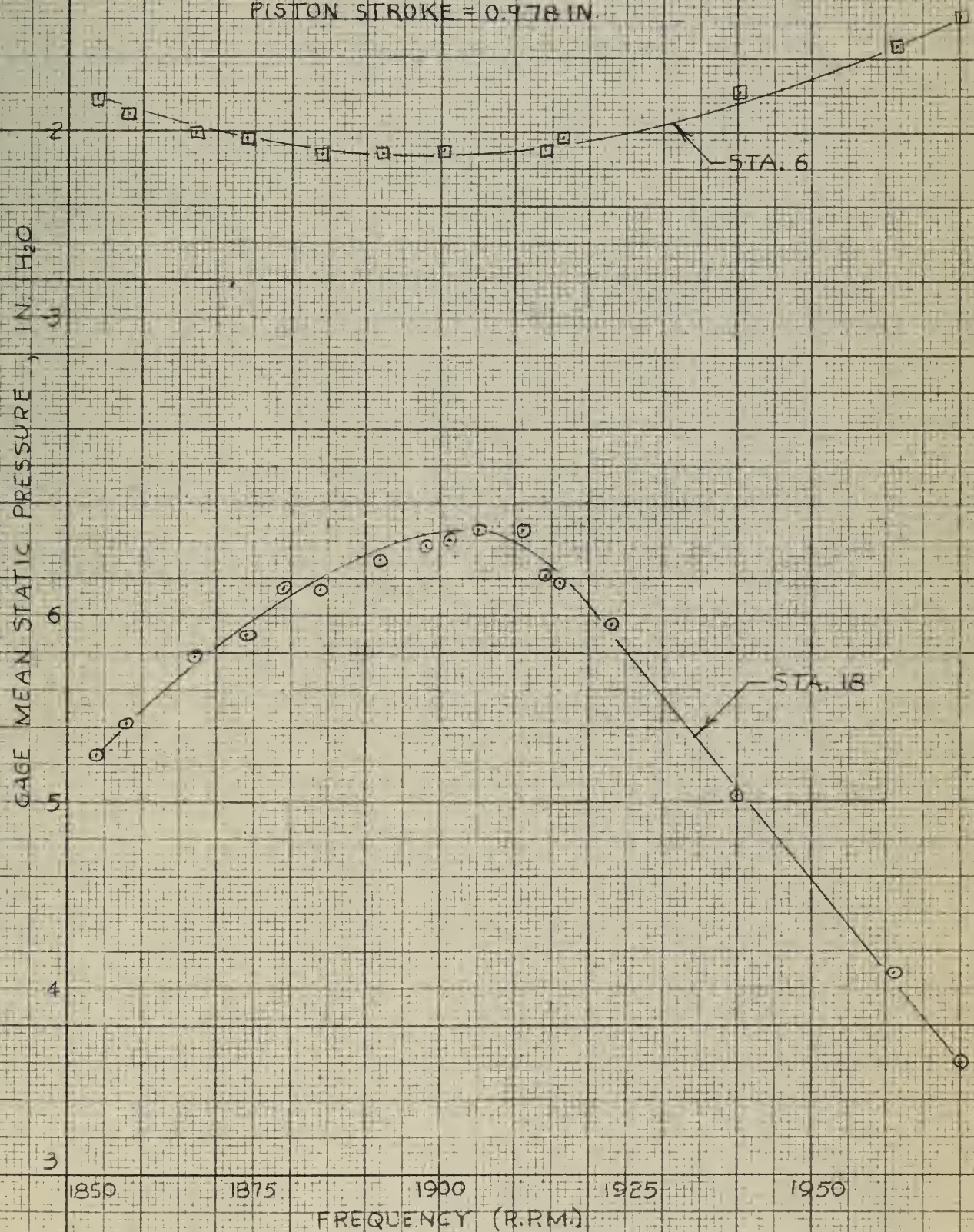


FIG. 14 DETERMINATION OF RESONANT R.P.M.
FOR TAPERED LIP RESONATOR CONFIGURATION
(TWO INCHES ADDITIONAL LENGTH)

(DATA FROM TABLE II)

PISTON STROKE = 0.978 IN.

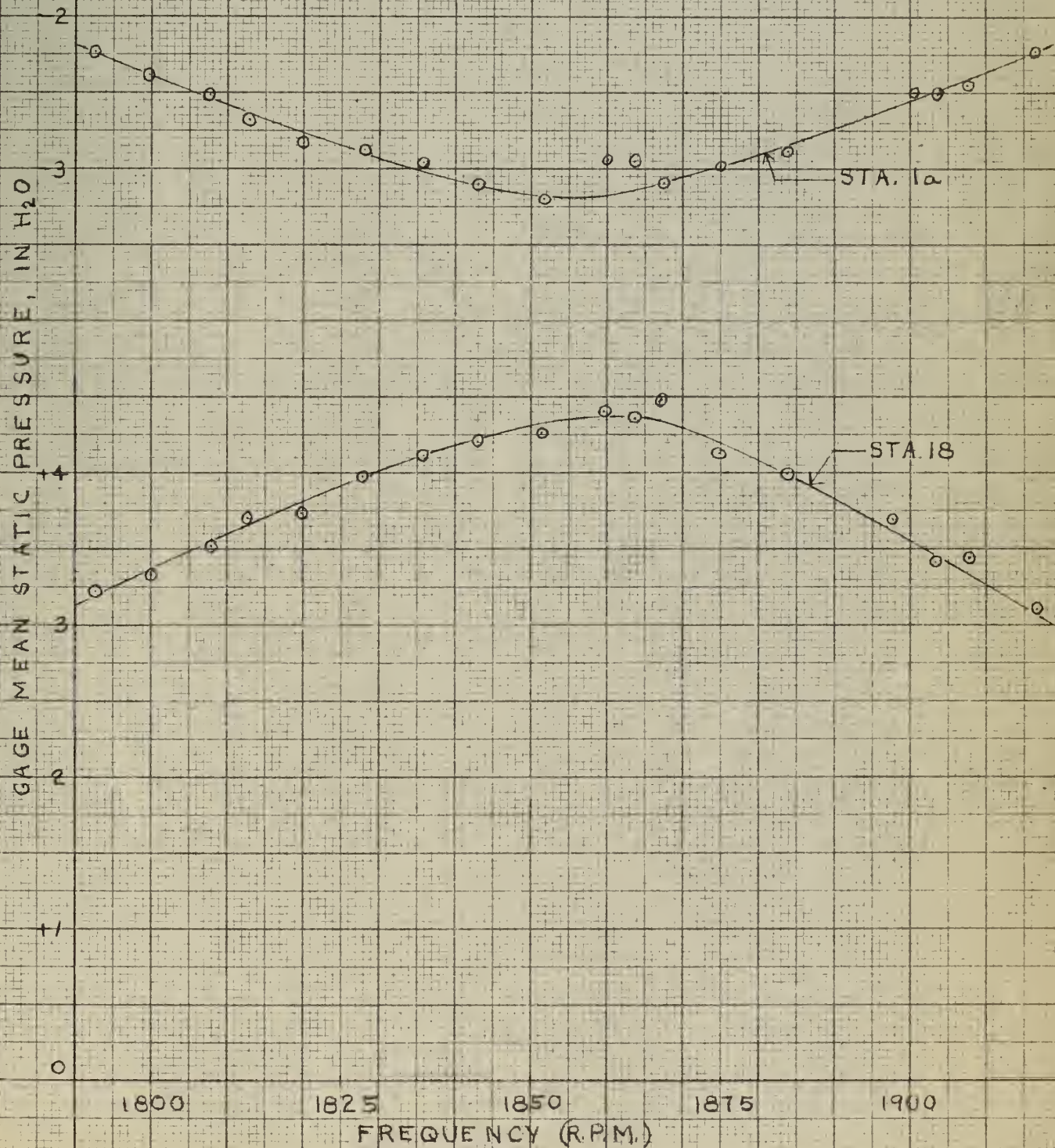


FIG. 15 THRUST FOR BASIC RESONATOR CONFIGURATION
(DATA FROM TABLE VI)

$L = 107.4 \text{ IN.}$

$D = 5.5 \text{ IN.}$

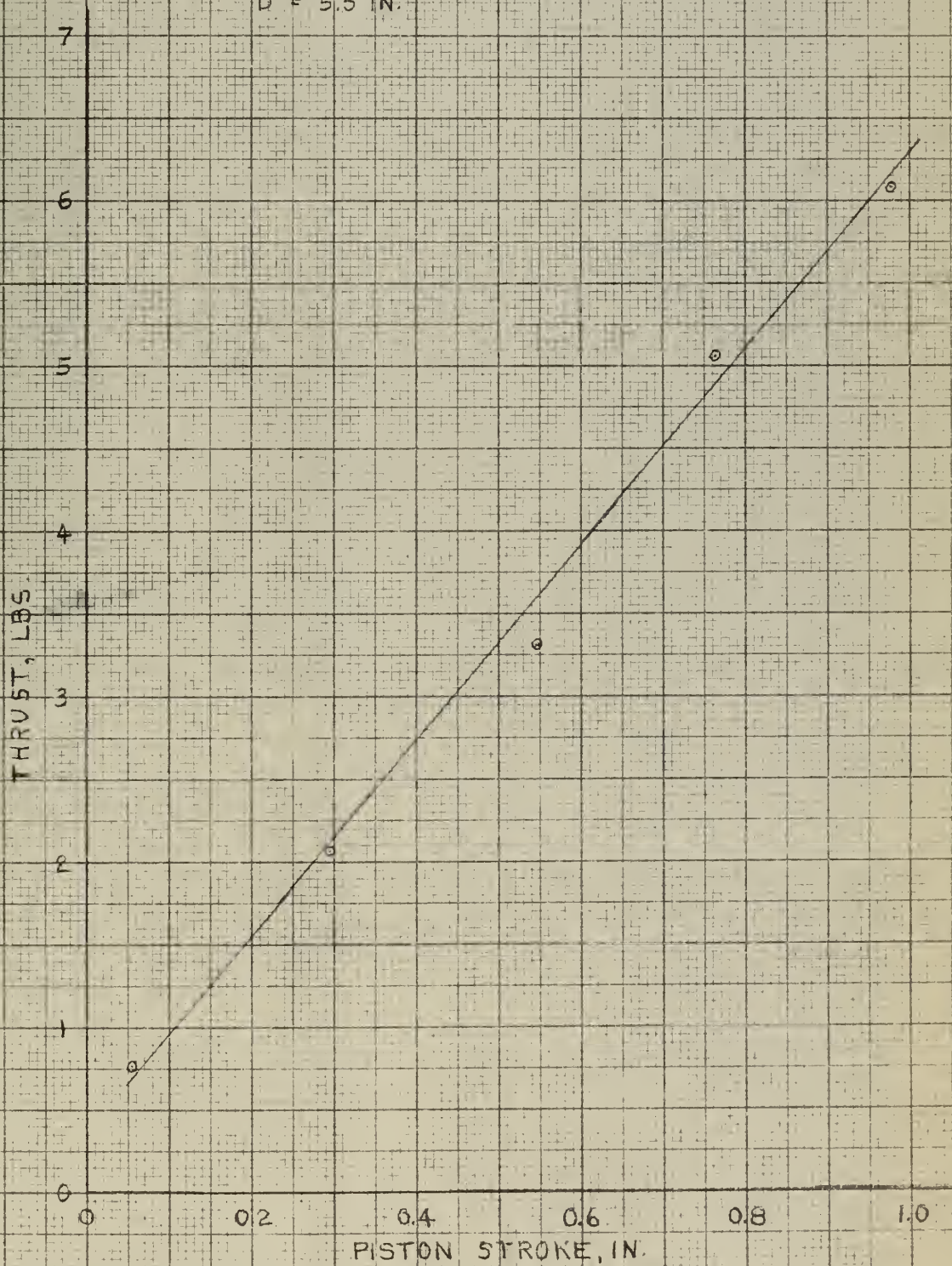


FIG. 16 INTERNAL RADIAL TRAVERSE,
MEAN STATIC PRESSURE
(DATA FROM TABLE VII)
PISTON STROKE = 0.978 IN.

$\bigcirc = 0^\circ$
 $\times = 180^\circ$
 $\square = 90^\circ$
 $\triangle = 270^\circ$

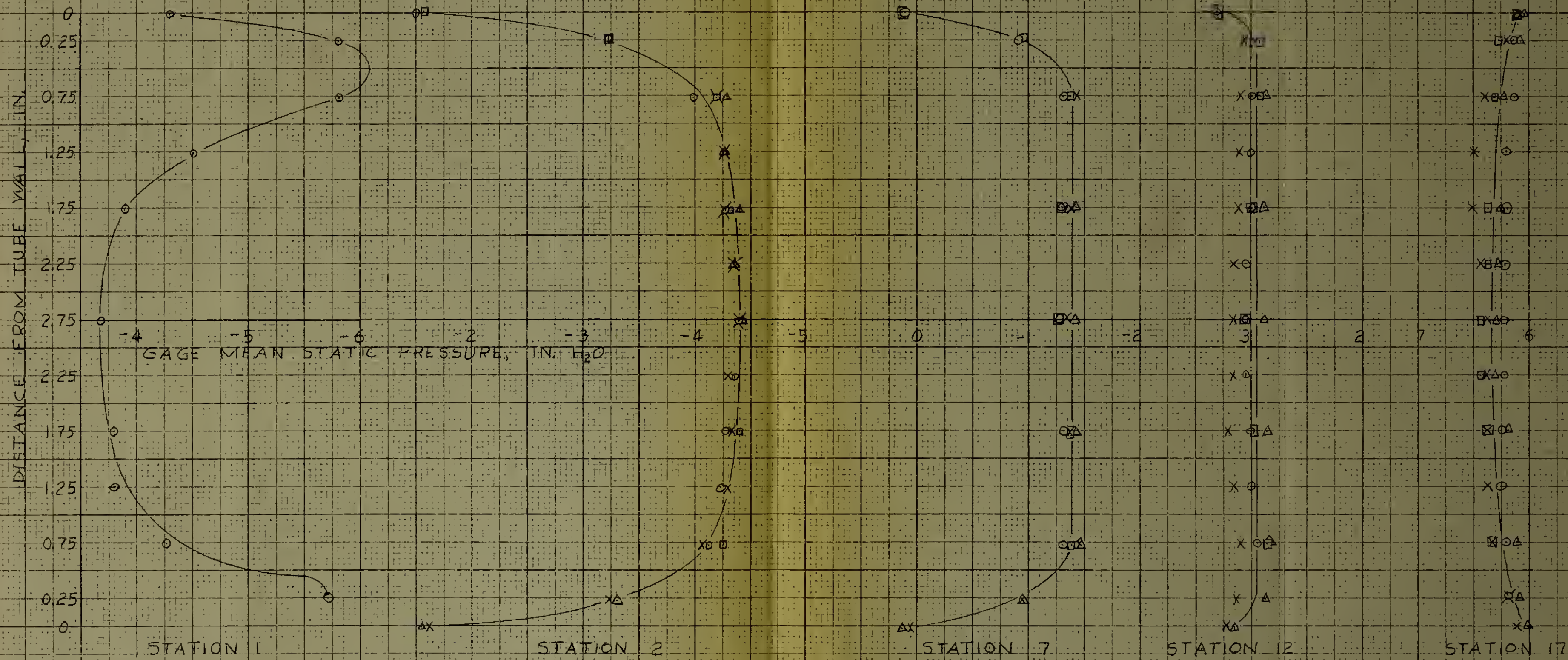


FIG. 17 MEAN PRESSURE PROFILES
IN DET OUTSIDE OF
RESONATOR OPEN END
(DATA FROM TABLES XIa, XIb)
PISTON STROKE = 0.978 IN.

DISTANCE FROM RESONATOR AXIS, IN

GAGE MEAN PRESSURE, IN H_2O

- GAGE MEAN STATIC PRESSURE
- ▽ GAGE MEAN TOTAL PRESSURE, FACING PISTON
- ◁ GAGE MEAN TOTAL PRESSURE, FACING AWAY FROM PISTON
- EXTERNAL DISTANCE FROM RESONATOR OPEN END, MEASURED ALONG CENTRAL AXIS, IN
- ▷ EXPERIMENTAL ERROR

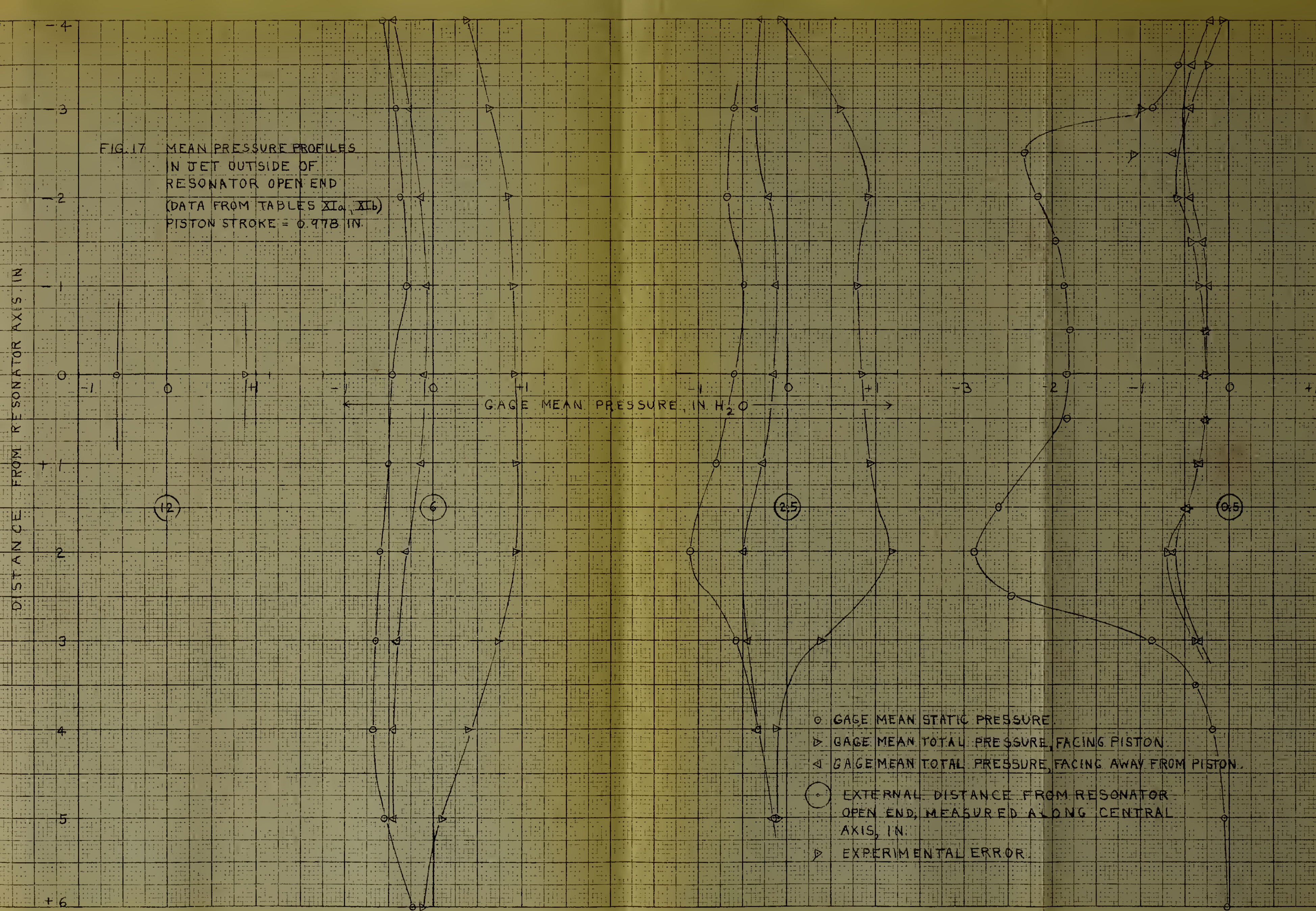
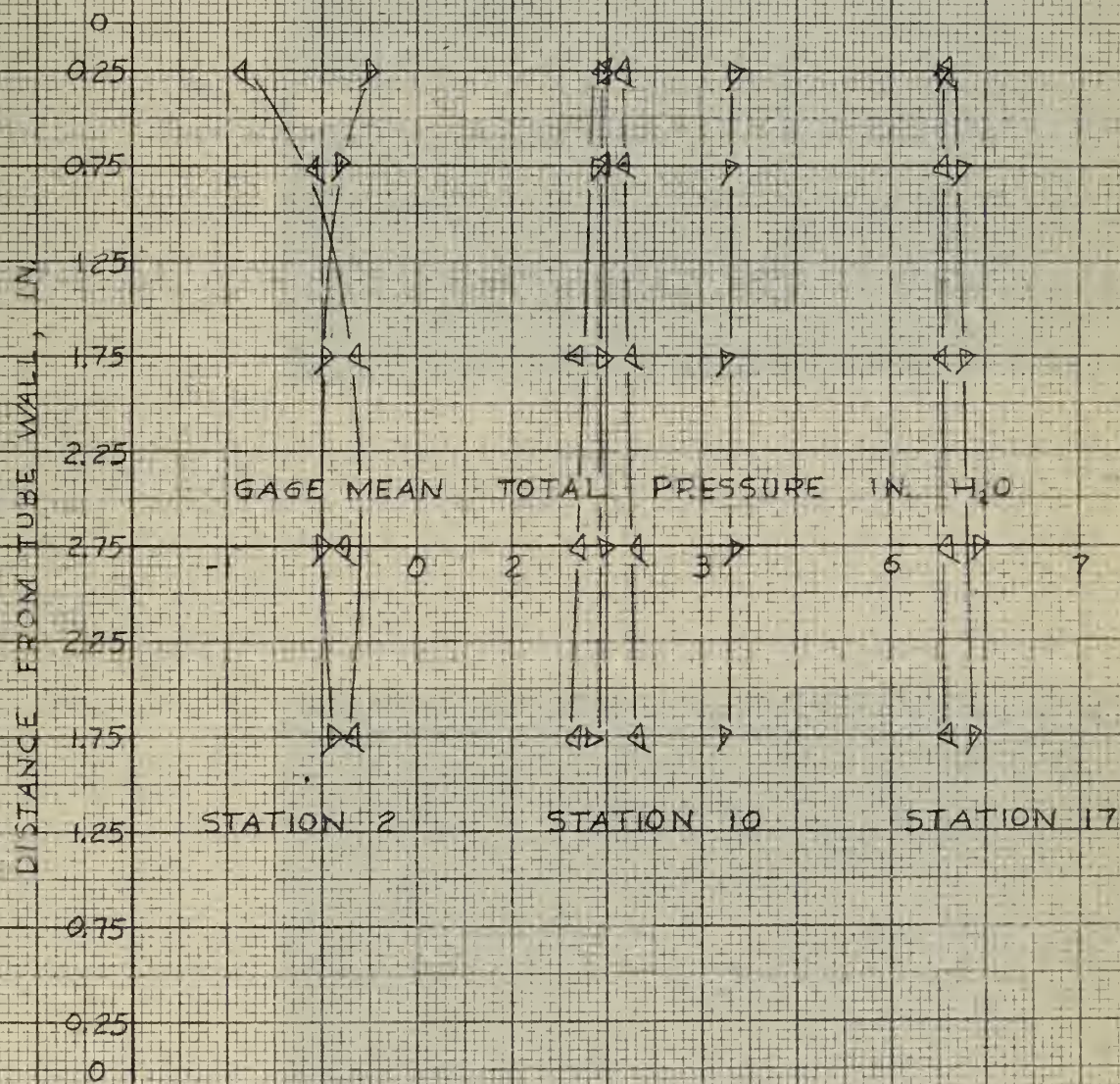


FIG. 18 INTERNAL RADIAL TRAVERSE
MEAN TOTAL PRESSURE
(DATA FROM TABLE IX)
PISTON STROKE = 0.978 IN.



△ = "L" TYPE TOTAL-HEAD PROBE FACING PISTON

◊ = "L" TYPE TOTAL-HEAD PROBE FACING AWAY FROM PISTON

▷ = CYLINDER TYPE TOTAL-HEAD PROBE FACING PISTON

◊ = CYLINDER TYPE TOTAL-HEAD PROBE FACING
AWAY FROM PISTON



Figure 10 - A view of the telescope from the side showing the segmented structure.



Figure 11 - A view of the telescope from the end showing the granular material inside.



A photograph of the comet 1956-1957
 taken on 1956-1957



A photograph of the comet 1956-1957
 taken on 1956-1957



Figure 10. A bright, horizontal, cloud-like or smoke-like plume against a black background.

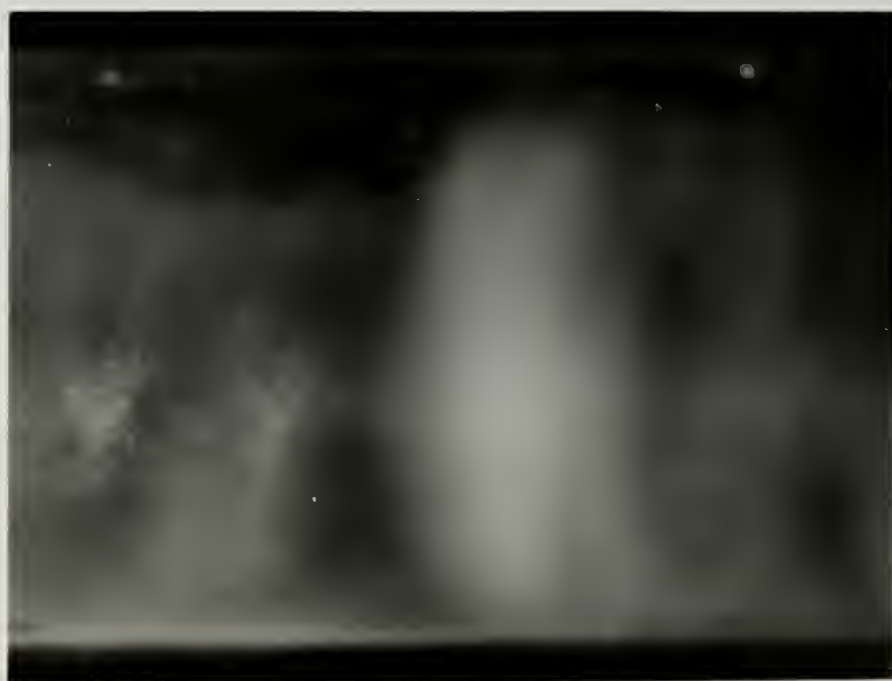


Figure 11. A bright, vertical, cloud-like or smoke-like plume against a black background.



Plume of smoke from the engine of the
U.S.S. Albatross



Plume of smoke from the engine of the
U.S.S. Albatross

FIG. 27 VARIATION OF DEPTH OF PENETRATION
OF RESONATOR, BY END VORTEX SYSTEM,
WITH MAGNITUDE OF PISTON STROKE.

(DATA FROM TABLE XII)

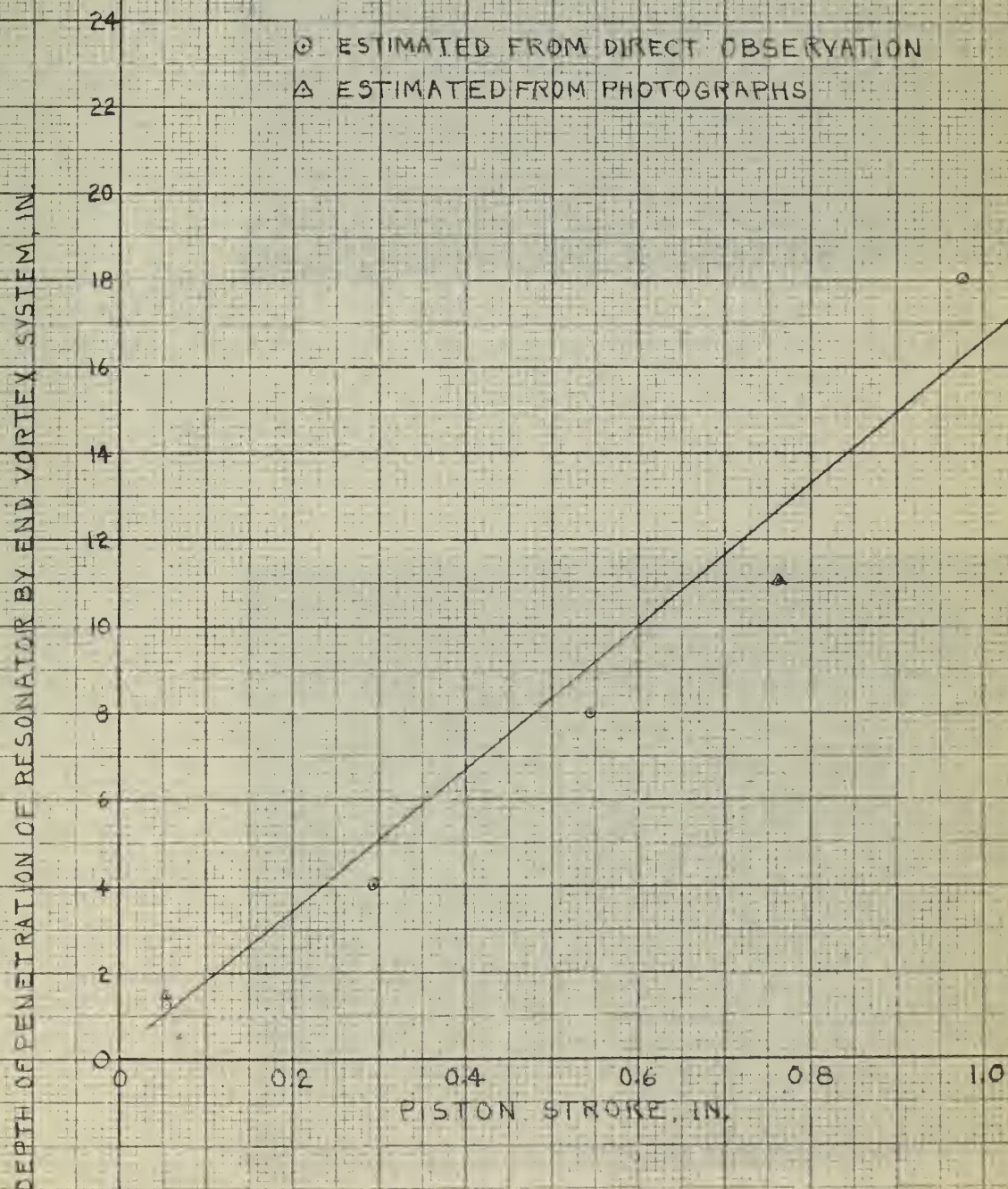




Figure 1. A bright, horizontal streak of light or smoke, possibly a fire or explosion, against a dark background.



Figure 2. A bright, horizontal streak of light or smoke, possibly a fire or explosion, against a dark background.

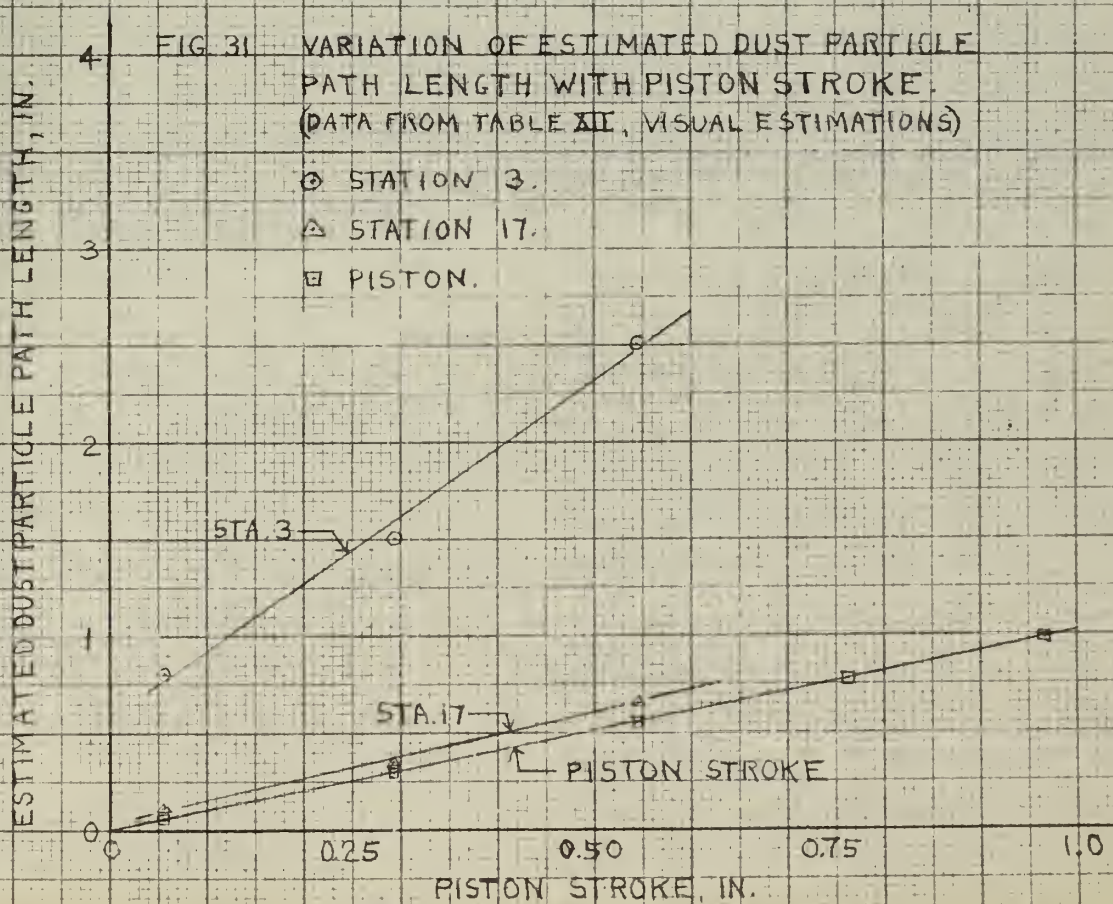
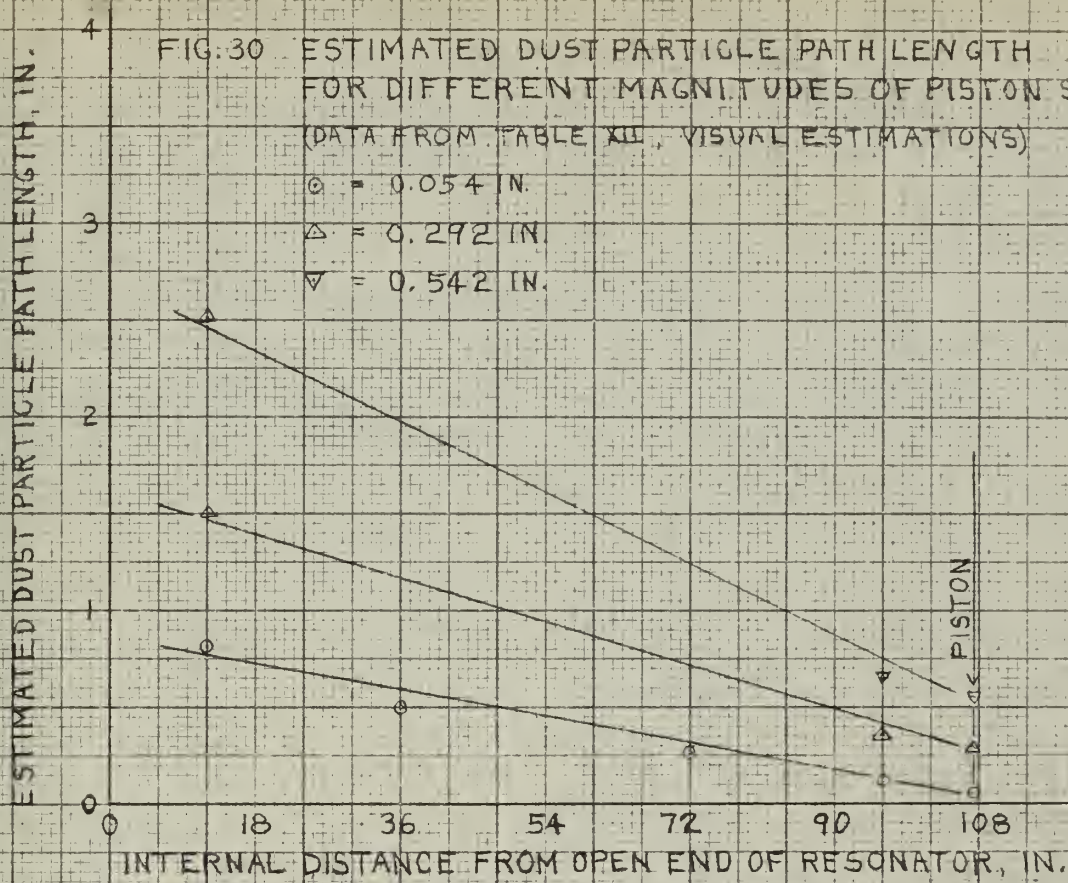
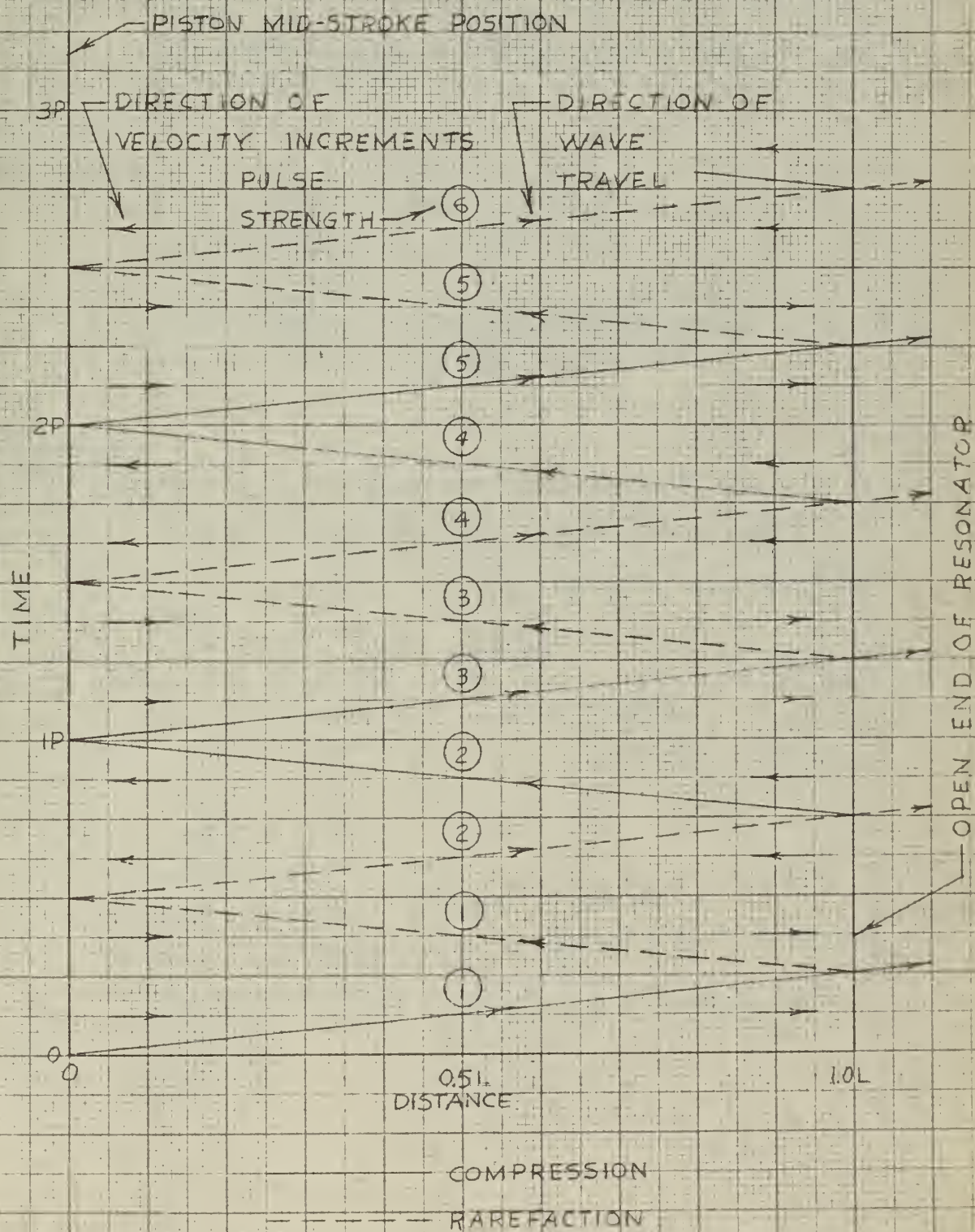


FIG 32 IDEALIZED TIME-DISTANCE DIAGRAM OF
WAVE PROGRESS IN A RESONATOR
CLOSED AT ONE END BY A PULSATOR
AND OPEN AT THE OTHER END



SAMPLE CALCULATIONS

RESONATOR FREQUENCY:

$$\pi = 2.75 \text{ in.}; L = 107.4 \text{ in.}; t = 88^\circ \text{F (Table I)};$$

$$f = \frac{12 \cdot 1148}{4[107.4 + 0.6(2.75)]} = 31.63 \text{ c.p.s.} = 1898 \text{ R.P.M.}$$

VELOCITY:

$$h_o = -0.67 \text{ in. H}_2\text{O (Table X, Sta. 1)}$$

$$h_s = -3.68 \text{ in. H}_2\text{O (Table VIII, Sta. 1)}$$

$$V = \sqrt{\frac{2(p_o - p_s)}{\rho}} = \sqrt{\frac{2(64.2)(3.68 - 0.67)}{(12)(0.002378)}} = 116 \text{ ft./sec.}$$

THRUST:

$$H_a = 29.42 \text{ in. Hg} = 400 \text{ in. H}_2\text{O (Table V)}.$$

$$h_{s(\text{piston})} = h_{sp} = +6.6 \text{ in. H}_2\text{O (Fig. 8, uncorrected)}$$

$$h_{s(\text{open edge})} = h_{se} = -3.6 \text{ in. H}_2\text{O (Fig. 8, uncorrected)}.$$

$$T = p_{sp} \cdot A_p + p_{se} \cdot A_e - p_a \pi(3)^2$$

$$p_{sp} = \text{absolute pressure on piston, lbs/in.}^2$$

$$p_{se} = \text{" " " open-end edge, lbs/in.}^2$$

$$p_a = \text{" " " atmospheric assumed acting externally on unit.}$$

$$A_p = \text{piston area} = \pi(2.75)^2 = 23.80 \text{ in.}^2$$

$$A_e = \text{open-end edge area} = \pi(3)^2 - A_p = 4.48 \text{ in.}^2$$

$$T = \frac{62.4}{12 \cdot 144} [406.6(23.8) + 396.4(4.48) - 400(28.28)]$$

$$= 6.06 \text{ lbs.}$$



5/9

DATE DUE

[illegible]

Thesis
J28

Janes

16259

Investigation of the
air-flow in an acous-
tic jet a resonance.

Thesis
J28

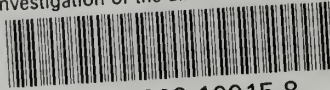
Janes

16259

Investigation of the
air-flow in an acous-
tic jet a resonance.

/thesJ28

Investigation of the air-flow in an acou



3 2768 002 10015 8

DUDLEY KNOX LIBRARY